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DIESEL SMOKE METERS FOR ARMY USE.(U)

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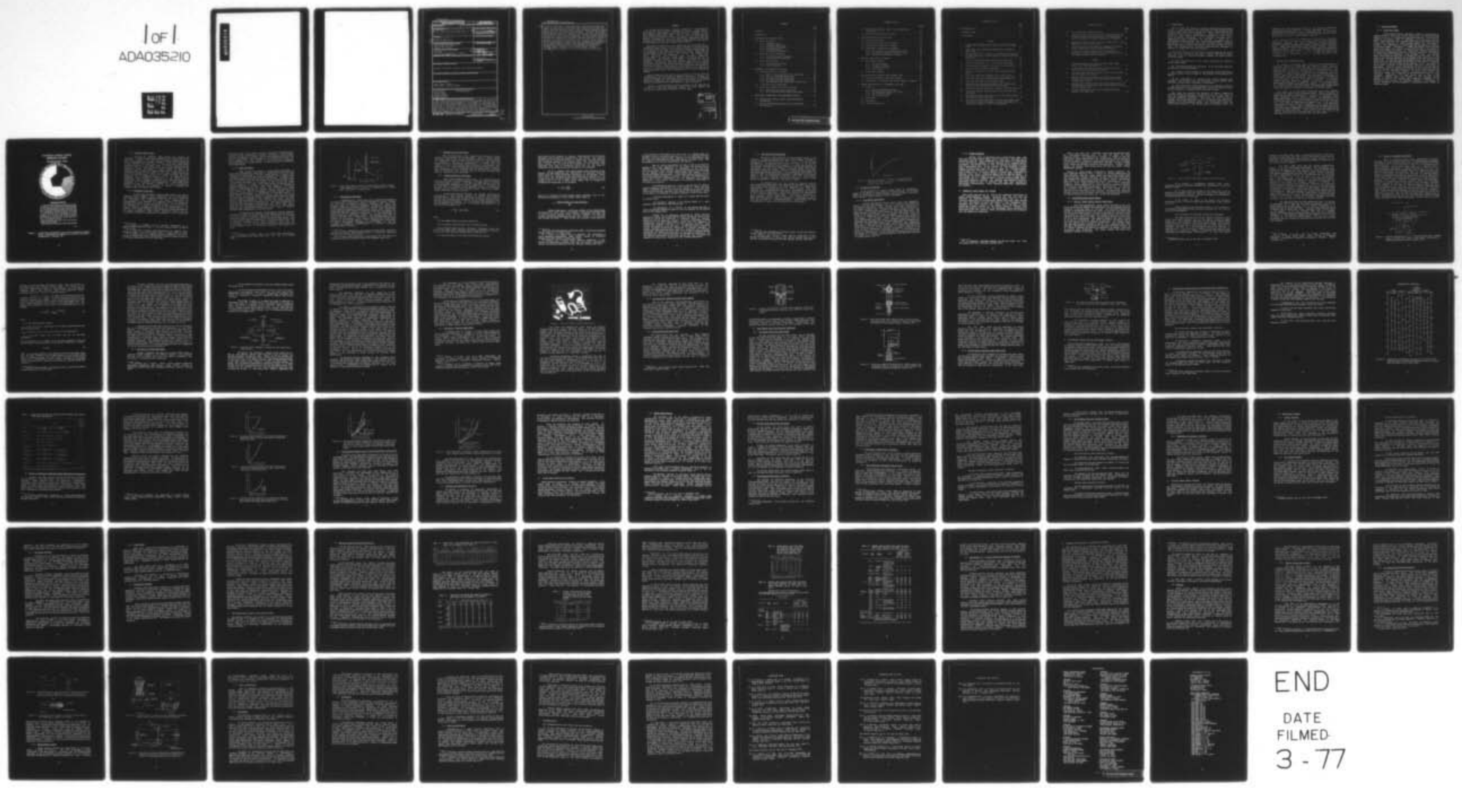

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A study was performed to determine the suitability of existing diesel smoke measuring equipment and techniques for Army use in a program of diesel smoke abatement. Most commercial equipment and virtually all known techniques were considered in view of possible enforcement, maintenance, or training applications. Attempts were made also to critically evaluate the particular nature of the Army smoke problem so that recommendations could be presented in a realistic perspective. This report gives a detailed summary of the

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results of this study. Smoke measuring techniques and available commercial equipment are reviewed, and technical criticisms are given. Previous overall studies of the technical aspects of smoke measurement also are reviewed and compared. Existing smoke abatement programs, including Federal and State, and their associated inspection procedures are examined, and attempts at their technical and practical evaluation are presented. The Army smoke problem is examined by reviewing the available technical studies of the problem and by considering information obtained from various knowledgeable individuals through interviews. Several novel techniques for the measurement of diesel smoke are suggested for consideration. These techniques address the problem of a permanently installed device that can give a continuous indication of a vehicle's smoke emissions on a dashboard meter. Finally, recommendations are given in view of the results of the study.

FOREWORD

In the body of this report, various statements of evaluation and criticism are made relative to commercial products (smoke meters). These remarks are not based on technical evaluations performed at the Harry Diamond Laboratories (HDL). Rather, they represent opinions expressed in the literature cited in this report, and in interviews with various individuals who have had considerable experience with the instruments in question. We believe that a representative cross section of these views is accurately conveyed by this report.

Opportunity is taken here also to thank the many individuals who, in discussions, gave of their time and expert knowledge on various aspects of the diesel smoke problem. We thank Wesley VanNess, Donald Suchy, and Bill Sommerson of the MERDC laboratories, Ft. Belvoir; LeRoy Higdon of the Environment Protection Agency (EPA) Engine Test Laboratory, Ann Arbor; John Elston and Andrew Bara of the New Jersey EPA; Vincent Labasio of the New Jersey Public Utilities Commission; Karl Springer, Alan Johnston, Frank Newman, and John Russell of the Southwest Research Institute, San Antonio; Jim Perry of Celesco Industries; Joe Calhoun, John Chao, and Paul Newmark of the California Air Resources Board; Ralph George and Roberts Lippner of the Los Angeles County Air Pollution Control District; John Robotti and Leo Belletti of the Ft. Ord Vehicle Maintenance Division, Monterey; K. L. Kane of the California Highway Patrol; and George Mackey of the Clayton Dynamometer Company.

Special thanks are due also to various members of the HDL staff who contributed to the work; Zoltan G. Sztankay and Robert G. Humphrey, who gathered information and contributed ideas on new methods of measuring smoke; and Lyndon Cox, who coordinated the early stages of the program and also contributed ideas on new methods for smoke measurement.

Finally, we thank Tom Reeves and Robert Woodward of the TMDE section of the U.S. Army Tank Automotive Command for their support and assistance in setting up and carrying out this study.

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FIGURES (Cont'd)

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1. INTRODUCTION

The U.S. Army has a need for a field-use smoke-metering instrument to aid in the maintenance of its large fleet of diesel-powered wheeled vehicles, both in the United States and abroad. These vehicles emit excessive smoke when out of adjustment or subjected to poor driving technique. This smoke is objectionable to humans and could violate local air-quality regulations. It is therefore desirable that a simple-to-use field instrument be provided to allow for a self-monitoring capability so that repairs and adjustments can be made when needed. It is desirable also that military drivers develop a greater awareness of visible smoke emissions and drive properly to avoid them. The availability of a field-use smoke-metering instrument is expected to promote such increased awareness.

The state of the art and availability of smoke meters for use by the Army has been studied by the Harry Diamond Laboratories (HDL). Sponsored by the U.S. Army Tank Automotive Command, the study consisted of the following:

(a) The identification of the various techniques for measuring diesel exhaust smoke

(b) The identification and evaluation of the available commercial instruments for such measurements

(c) A review of the literature on the problem of smoke measurement, including previous overall studies of the problem, and discussions with experts

(d) The establishment of contacts with various agencies, both government and private, that are attempting to control mobile smoke emissions, through either enforcement or maintenance

(e) The investigation of the feasibility of a permanently installed on-board smoke meter with a dashboard meter readout, for driver training and the promotion of increased driver awareness of smoke.

This study has revealed the existence of several commercially available portable smoke meters intended for field use that appear to have the requisite ruggedness, reliability, and accuracy for the intended maintenance application. This study has also determined, however, that serious questions exist as to whether maintenance alone, employing one of these smoke meters, will sufficiently reduce the visible smoke emissions of Army diesel trucks to acceptable levels. The

inherently poor smoke performance of many of the vehicles, coupled with generally poor driving technique, is probably the major source of the objectionable smoke emitted. If so, a smoke meter that is permanently installed on the vehicles, perhaps only on the training vehicles, would be required to generally improve driving technique.

This report summarizes the information and conclusions established during this study. Sections 2 to 4 describe and discuss smoke measuring techniques, equipment, and their associated technical problems. Section 5 describes the methods of testing a vehicle's smoke performance with a smoke meter and evaluates their relative validity. Section 6 summarizes Federal, State, and municipal enforcement and maintenance programs to limit diesel smoke. Section 7 discusses and evaluates the Army's problems of smoke control. Section 8 summarizes overall and considers various alternative solutions. Finally, section 9 lists recommendations.

2. TECHNIQUES FOR MEASURING SMOKE

The problem of measuring smoke has led to a great diversity of measurement techniques, ranging from the relatively simple and crude ones represented by the use of Ringelmann charts to sophisticated ones employing optical systems or analytical-chemical determinations of soot concentration. Operationally, the techniques can be grouped into three categories: (1) *Remote methods* include the use of Ringelmann charts and filmstrip smoke guides, photographic and photometric techniques, and lidar (laser radar) methods and are characterized by being performed in a location remote from the smoke plume of interest. (2) *Proximate methods* typically depend on optical transmission or scattering measurements performed in the immediate vicinity of the smoke source. (3) *Filtration methods* typically involve drawing a known volume sample of the smoke through a filtration medium and subsequently analyzing the filter for either the darkness of the deposit or the soot weight.

The reason for this diversity of techniques lies in the different interests that people have in measuring smoke. Agencies interested in monitoring industrial smokestacks or in enforcing on-road diesel vehicle smoke regulations have a natural interest in developing remote measurement methods. On the other hand, diesel engine manufacturers and certain enforcement groups want to evaluate smoke production in engine test cells, where the smoke-measuring apparatus has to be physically integrated with other evaluation equipment. Also, fleet maintenance units require a garage type of smoke-measuring instrument that can be used with a chassis dynamometer or some other form of prescribed driving schedule for smoke evaluation. Other interests, such as evaluating the smoking characteristics of various types of fuel, have led to the development of still other techniques for evaluating smoke.

2.1 Remote Techniques

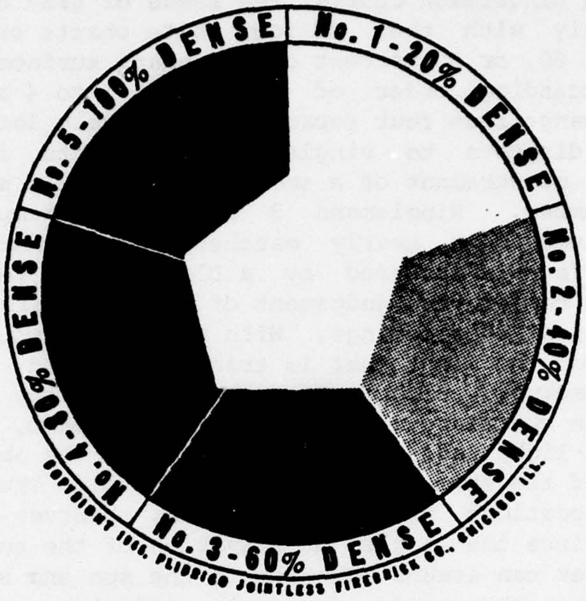
2.1.1 Ringelmann Charts

With Ringelmann Charts, the shade of gray of a smoke plume is compared visually with that of four white charts on which black grids obscure 20, 40, 60, or 80 percent of the chart surfaces. The charts are numbered, in ascending order of darkness, 1 to 4 and come in various forms. These range from four separate relatively large charts that can be seen from a distance to single pocket charts like that shown in figure 1. The measurement of a smoke plume by this method is stated as a Ringelmann number. Ringlemann 3 smoke, for example, means that the shade of the plume most nearly matches that of chart 3, 60 percent of whose white surface is obscured by a black grid. Besides depending on an individual's comparative judgement of visual qualities, this method has other technical shortcomings. With the smoke plume, the observed shade arises from the light that is transmitted and scattered by the plume to the observer, primarily from a region of the sky in back of the *smoke plume*. In contrast, with the Ringlemann chart, the observed shade arises from the light reflected by the chart to the observer, primarily from a region of the sky in back of the *observer*. Thus, variations in the relative locations of the smoke plume, observer, or sun change the measurement. Since the angle of elevation of the sun and the position that the observer can assume relative to the sun and smoke plume are not entirely at the observer's disposal, and since other factors can critically modify the conditions of the measurement (such as cloud locations), compensation for these factors must be left to the observer's judgment. Thus, the validity of the Ringlemann method depends as much on the training and intelligent judgment of the practitioner as it does on the technical details of the method. It should, therefore, not be considered a technically sound method of measuring smoke.

CALIFORNIA HIGHWAY PATROL

SMOKE CHART

RINGELMANN TYPE



INSTRUCTIONS

1. The scale should be held at arm's length at which distance the dots in the scale will blend into uniform shades.
2. Then compare the smoke (as seen through the hole) with the chart, determining the shade in the chart most nearly corresponding to the shade or density of the smoke.
3. A motor vehicle shall be considered to be emitting "excessive" smoke, gas, oil or fuel residue if on visual comparison for a reasonable period the exhaust products have a density that is equal to or greater than No. 2 (40%) on the Ringelmann Chart.

Observer should not be less than 100 feet nor more than 500 feet from the vehicle.

Observer should avoid looking towards bright sunlight.

Δ osp

Figure 1. Pocket-sized Ringelmann chart used by California Highway Patrol (reproduced by permission of Plibrico Jointless Firebrick Co., Chicago, IL).

2.1.2 Filmstrip Smoke Guides

The use of filmstrip smoke guides also involves the evaluation of smoke through visual comparison of the smoke plume with a gray scale. However, the gray scale is produced by gradations in the optical transmission of a plastic filmstrip, rather than by gradations in the reflectance of opaque charts. In the use of such a smoke guide, the shade of gray of the smoke plume is visually compared with the shades of gray of the guide when it is held so that the region of sky immediately beside the plume is viewed through the guide. The comparison here is between the apparent opacity of the plume and that of the various sections of the guide to the light coming from the sky behind and near the plume. Thus, this method overcomes the major objections to the Ringelmann method. In fact, as demonstrated by experiment, this technique is insensitive to the various factors influencing general lighting conditions that do produce substantial variations in a Ringelmann chart measurement.[1,2] This method can be employed by using any suitable collection of optical transmission filters, and the use of filmstrips is merely a convenient and inexpensive way of obtaining such filters.

2.1.3 Photometric Techniques

As their major drawback, filmstrip smoke guides still require subjective visual judgment. Various elaborations of the principle of such smoke guides, using photometric techniques, have been considered for overcoming this limitation.[3] In these elaborations, by telephotometry, the luminance of background objects is objectively measured both through and clear of the smoke plume. In one elaboration, the luminance of a bright background object, such as the sun, is measured through the plume and clear of it. The transmittance of the plume is then simply obtained as the difference of these measurements. In another elaboration, where bright background objects are not conveniently available, one measures the luminance of two contrasting

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[1] *A. H. Rose, J. S. Nader, and P. A. Drinker, Development of an Improved Smoke Inspection Guide, J. Air Poll. Control Assoc., 8 (August 1958), 112-116.*

[2] *A. H. Rose and J. S. Nader, Field Evaluation of an Improved Smoke Inspection Guide, J. Air Poll. Control Assoc., 8 (August 1958), 117-119.*

[3] *W. D. Conner and J. R. Hodkinson, Optical Properties and Visual Effects of Smoke-Stack Plumes, Environmental Protection Agency Office of Air Programs Publication No. AP-30 (May 1972).*

background targets both through and clear of the plume (this measurement gives the plume transmittance somewhat indirectly). These methods overcome the subjective element present with smoke-guide measurements, but are considerably less convenient and more expensive to use. The major drawback with these methods is in finding the appropriate background objects or, alternatively, in having to modify the technique with circumstances.

2.1.4 Lidar Techniques

Lidar methods that provide a single-ended measurement of smoke plume transmittance, independent of background objects, have been proposed and investigated.[4] The basic system employs a pulsed laser transmitter (a Q-switched ruby laser, for example) and a photomultiplier tube (PMT) detector (receiver) situated side by side. A single laser pulse is directed toward the smoke plume, and the backscattered return is monitored (recorded) as a function of time via the PMT signal voltage. Figure 2, an ideal lidar signal return, illustrates how the plume transmittance is obtained. The return begins to decrease as $(\text{range})^{-2}$, corresponding to the general lidar equations, at a range beyond which the transmitter and receiver fields fully overlap (about 100 m in fig. 2). This $1/r^2$ performance continues, provided that the atmospheric backscattering is homogeneous and the range interval is small enough to neglect extinction effects. When the laser pulse intercepts the smoke plume, however, the backscattered signal increases above the ambient atmospheric level, appearing as a spike on the lidar return. Light backscattered to the receiver from ranges beyond the plume will have been twice attenuated by it. Thus, the transmittance of the plume can be obtained by extrapolating the signals from just in front of and just beyond the plume (as $1/r^2$) to a common range, obtaining the extrapolated signal levels A and B shown in figure 2. Then the plume transmittance is given by $(A/B)^{1/2}$.

In practice, the intense backscattering from the plume has been found to cause PMT afterpulsing in the region following the plume, as well as causing the system's amplifying electronics to be driven sufficiently hard to produce slow signal recovery in that region.[4] Each of these factors tends to produce error in the extrapolated signal level A, generally resulting in too high a measured value for the transmittance. It has, however, proved possible to reduce these errors to an acceptable level by introducing appropriate off gating of the PMT.[4]

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[4]C. S. Cook, G. W. Bethke, and W. D. Conner, Remote Measurement of Smoke Plume Transmittance Using Lidar, Appl. Opt., 11, No. 8 (August 1972).

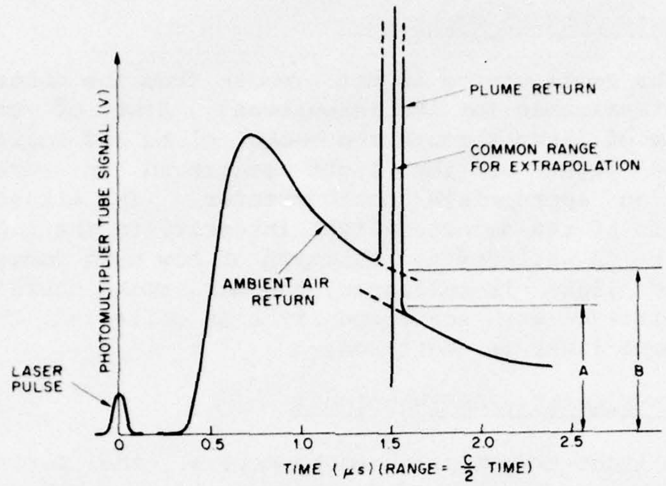

Figure 2. Ideal lidar signal return for single-pulse incident on smoke plume (adapted from C. S. Cook, G. W. Bethke and W. D. Conner, Appl. Opt. 11 No. 8 (August 1972)).

2.1.5 Photographic Techniques

A photograph of a smoke plume can be compared instrumentally or visually with an established scale of blackness or opacity. Between 1965 and 1967, a Society of Automotive Engineers (SAE) task force actively sought to establish acceptable procedures to measure and document diesel smoke using photography.[5,6] The SAE found that although it is technically possible to measure diesel exhaust smoke density from photographs made under carefully controlled conditions, the procedure is tedious and involves frequent calibrations. So that photography can yield accurate and reproducible results, the exposed film must be measured precisely with a densitometer. Then the measurements must be related, via calculations, to the exposure characteristics of the film, typically in the nonlinear region of this characteristic. With regard to simpler photographic procedures, it was concluded that they are incapable of sufficient reproducibility to provide a reliable smoke-measurement technique.

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[5] *A. W. Carey, Steady-State Correlation of Diesel Smoke Meters--An SAE Task Force Report, Paper 690492, Society of Automotive Engineers, Mid-Year Meeting, Chicago (May 1969).*

[6] *Diesel Engine Smoke Measurement (Steady-State) SAE J255, Society of Automotive Engineers Information Report, SAE Handbook (June 1971).*

2.2 Proximate Optical Techniques

When the smoke source is not remote from the observer, various techniques are available for its measurement. Most of these involve directing a beam of light through the smoke plume and collecting either the transmitted light or the light scattered in some particular direction with an appropriate photodetector. In either case, one expects the ratio of the detected light intensity to the incident light intensity to be a well-defined function of how much smoke is present. When transmitted light is collected, the more smoke there is, the less light is transmitted. When scattered light is collected, the more smoke there is, the more light is scattered.

2.2.1 Light-Transmission Techniques

With light-transmission smoke meters, the percentage of the incident light that is blocked (opacity) is usually taken as a measure of how much smoke is present. On one hand, the smoke opacity is related to the subjective judgment of the visual appearance of the smoke. On the other hand, it is related to the objective factor of soot weight density. It thus appears to be a suitable measure. There are, however, several subtleties in these relations.

The following briefly describes the relevant theory of the transmission of light through aerosols, to clarify the relations discussed above. When a beam of light passes through an aerosol such as smoke or fog, scattering and absorption by the aerosol particles cause the beam intensity to diminish. If the incident light intensity is I_o and the emergent light intensity is I, the aerosol transmittance, T, is given by the Beer-Lambert law:

$$T = \frac{I}{I_o} = \exp(-n\bar{a}\bar{Q}t) \quad , \tag{1}$$

where

n is the number density of aerosol particles,

$\bar{a}$ is an average cross-sectional area of single particle,

$\bar{Q}$ is an average single particle extinction efficiency factor (the ratio of the total light intensity scattered and absorbed by a particle to the total light intensity geometrically incident on it),

t is the path length of the light beam through the aerosol.

The factors $\bar{a}$ and $\bar{Q}$ depend on various characteristics of the aerosol particles, such as their size distribution and shapes. The factor $\bar{Q}$ depends also on the particle indices of refraction, and both depend on the wavelengths present in the incident light. This dependence comes about because (1) the ratio of the wavelength to the particle size determines what type of scattering occurs and (2) the index of refraction of the aerosol particles depends on the wavelength.

If it is assumed that diesel exhaust smoke exhibits, on the average, the same composition and distribution of particle sizes and shapes, then for a fixed wavelength distribution in the incident light, only n and t are variables on the right-hand side of equation (1). It is then clear that the soot-weight density (the weight of soot in a unit volume of air), M, of a given smoke sample can be related to a transmittance measurement by the equation

$$M = \frac{A}{t} \ln \left(\frac{1}{T}\right), \tag{2}$$

where A is a constant for diesel exhaust smoke, dependent only on the wavelength distribution of the incident light, given by

$$A = \frac{\text{average weight of a soot particle}}{\bar{a}\bar{Q}} .$$

Several smoke-meter correlation studies in the United States and abroad have shown that it is possible to correlate M linearly with ln (1/T) for diesel exhaust smoke, making allowances for only the incident wavelength distribution and the path length, t, of the light beam through the smoke.[7-9] These studies are reviewed in more detail in

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[7] *1967 CRC Diesel Smokemeter Calibration Tests, Coordinating Research Council Report No. 421 (June 1969).*

[8] *F. J. Hills, T. O. Wagner, and D. K. Lawrence, CRC Correlation of Diesel Smokemeter Measurements, Paper 690493, Society of Automotive Engineers Mid-Year Meeting, Chicago (May 1969).*

[9] *F. Pinolini and J. Spiers, Diesel Smoke--A Comparison of Test Methods and Smokemeters on Engine Test Bed and Vehicle, Paper 690491, Society of Automotive Engineers Mid-Year Meeting, Chicago (May 1969).*

a later section of this report; at this point, we simply draw the conclusion that A, as given by equation (3), is at least approximately constant for diesel exhaust smoke. Equation (2) can therefore be used as a basis for obtaining the soot-weight density of diesel smoke from measurements of its optical transmittance (or opacity).

When an opacity measurement of smoke is used as an objective measure of the visual appearance of the plume, two cautions must be observed. First, the distribution of wavelengths in the test light must, on the whole, have the same transmission properties through smoke as the ambient light in which smoke plumes are viewed. If the wavelengths differ substantially, a correlation between measured opacity and visual appearance cannot be expected. Secondly, the appearance of a smoke plume varies considerably with the background and lighting conditions. It is, in fact, the purpose of an objective measurement to overcome this situation.

The differences among the various systems that are based on light-transmission measurements lie in the manner in which the smoke sample is obtained and in the choice and integration of the particular optical and electronic components that measure the transmission. Access to the smoke to be measured is generally obtained in one of three ways:

(a) Direct measurement of smoke as it issues from the end of the exhaust pipe

(b) Continuous sampling of the exhaust stream by a small sampling probe inserted in the exhaust pipe

(c) Replacement of a section of the exhaust pipe with a hollow cylindrical measuring chamber so that the exhaust can be measured while in the exhaust line.

Method (c) is especially convenient in engine test-cell applications where centralized exhaust removal systems are often in use. Methods (a) and (b) are convenient in measuring smoke on vehicles. Method (b) has the additional feature of giving a measurement of smoke transmission of a fixed length sample, rather than one depending on exhaust pipe diameter (see sect. 3.1.2 for additional details). Light sources are generally one of two types: incandescent bulbs, intended to crudely reproduce the spectral properties of ordinary daylight, or solid-state light-emitting diodes, which are generally more reliable, long-lived, and rugged, but emit light of very small wavelength spread. Photodetectors are selected primarily for appropriate sensitivity over the spectral distribution of the light source, and the electronics are designed in various ways, depending on the intended application.

2.2.2 Light-Scattering Techniques

The use of light scattering to measure smoke density is more difficult to describe theoretically, since the phenomena involved in optical scattering from aerosols are more complex than those of light transmission. The technical basis of the measurement is as follows. The ratio of the scattered-light intensity in a particular direction to the incident intensity is a linear function of the aerosol density, for low density. As the aerosol density increases beyond this range, extinction effects and, finally, multiple scattering become important, and deviations from linearity ensue. At sufficiently high density, the amount of light scattered becomes essentially independent of the aerosol density; that is, saturation is reached. Hence, the characteristic curve of scattered intensity in some fixed direction versus aerosol density is expected to look like that shown in figure 3.

An instrument based on this operation principle, called a light-dispersion smoke meter, which measures the scattering at 90 deg to the incident-beam direction, has been developed by Robert Bosch Laboratories. It has been difficult to obtain anything other than tentative data evaluating this instrument. Nevertheless, the readings obtained with this smoke meter tend to vary linearly with smoke density up to a carbon concentration of about 0.5 g/m^3 (which corresponds to about 15-percent opacity smoke from a 4-in. exhaust stack). Higher smoke densities require a nonlinear calibration.[9] The method appears to lack the accuracy of chemical-analytical determinations of soot concentration, at least in its current state of development.[7]

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[7] *1967 CRC Diesel Smokemeter Calibration Tests, Coordinating Research Council Report No. 421 (June 1969).*

[9] *F. Pinolini and J. Spiers, Diesel Smoke--A Comparison of Test Methods and Smokemeters on Engine Test Bed and Vehicle, Paper 690491, Society of Automotive Engineers Mid-Year Meeting, Chicago (May 1969).*

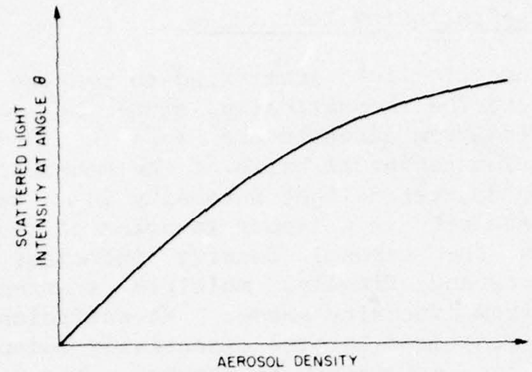

Figure 3. Expected qualitative variation of scattered-light intensity in fixed direction, θ, versus density of aerosol effecting scattering.

2.3 Filtration Techniques

In the evaluation of diesel exhaust smoke by filtration, a sample of the exhaust is passed through a suitable filter, and the smoke density is determined by either measuring the soot weight or evaluating filter darkness (either visually or with instruments).

2.3.1 Soot-Weight Measurement

Several laboratories (such as Ethyl Corp. and Caterpillar Tractor) have developed equipment and test techniques for determining the weight of particulate matter (mainly carbon-soot particles) in a unit volume of exhaust gas. In these techniques, a small vacuum pump is used with a sampling probe inserted in the exhaust stream to draw a gas sample through a suitable filter (usually a thin glass-fiber disc). The volume of the sampled exhaust gas is measured, the weight of the soot collected is determined by analytical methods, and the soot weight per unit volume is thus obtained. Since the sampling times involved in these measurements range from several seconds to as much as 2 min, the techniques are inappropriate for transient smoke density determinations. They are, however, quite accurate and reproducible for steady-state measurements. Two methods are in general use for the weight measurement of the collected soot. In one, the filter is weighed both before and after the soot is deposited; by heating, any moisture collected in the filter is driven off prior to the second weighing. In the other method, the weight determination is made chemically by burning the filter disc plus sample in a special laboratory apparatus and measuring the amount of carbon dioxide given off.

2.3.2 Filter Darkening

Another form of evaluation uses a white filter paper disc upon which the passed smoke sample leaves a gray spot. This spot can be evaluated either by visual comparison to a gray scale or by measurement of its reflectivity, compared to some standard, with a suitable optical instrument. The methods used to draw the exhaust gas sample with this form of measurement vary. In one version of this technique, a single sample of fixed volume (about 330 cm^3) is drawn by a spring-actuated, plunger-type pump connected to a sampling probe, with a total sampling time of about 0.6 s. In another version, a vacuum pump connected to a sampling probe draws a continuous sample from the exhaust stream. In this system, the filter paper is in the form of a roll of tape that is continuously fed to a sampling head, to record transient smoke levels. With filter darkening methods, the sampling time required to obtain a measureable amount of soot is decidely less than that required for soot-weight determinations; hence, transient smoke-level measurements are possible.

3. COMMERCIAL SMOKE METERS AND SYSTEMS

Very little need and can be said on the commercial availability of remote smoke-measuring systems. Virtually all that are used and available are Ringelmann charts. The basic reason lies not in any technical superiority of the Ringelmann method over other remote methods (in fact, the opposite is true), but rather in that Ringelmann chart standards have been written into almost all of the legal statutes pertaining to smoke control in the United States.[10] Besides, these charts are simple and of low cost, and enforcement bodies constitute the major market for such devices. Hence, Ringelmann charts are ubiquitous and lack commercial competition.

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[10]*D. D. Armstrong, Ringelmann Numbers and the Law, Paper 712, Proc. 27th Annual ISA Conf., New York (October 1972).*

Until a few years ago, a filmstrip smoke guide was available from the Environmental Research Corp., St. Paul, MN (Model 110 Smoke Inspection Guide). Also commercially available a number of years ago were various similar devices that are viewed against the sky through a collimating system. Photometric smoke measuring devices do not appear to have ever been available as commercially packaged systems, although their design and production would be relatively easy. Finally, lidar systems for probing smoke plumes exist, but they are rather complex experimental systems.

Outside of remote systems, availability changes radically. The first impression obtained from a survey of on-board smoke meters is their plenitude. Many such smoke meters have been given company names and have had test results published on them without their ever having been commercially available in a practical sense. Various experimental smoke meters of engine manufacturers and oil companies are in this category. Other smoke meters have had only a brief commercial existence, such as submissions to a state agency for evaluation relative to the agency's smoke-meter-requirements specifications. A criterion has therefore been employed to select the smoke meters that are described in the remainder of this section. All smoke meter types are covered; however, only instruments that have established some reputation for quality through actual sales, use, or both are described.

3.1 Light-Transmission Smoke Meters

3.1.1 The U.S. Public Health Service Smoke Meter

This light-transmission smoke meter, developed by the U.S. Public Heath Service (USPHS) and manufactured by the Southwest Research Institute, is the best known of its type. The instrument measures the opacity or transmittance of flowing smoke at a point a few inches from the end of the exhaust outlet. It does so by means of an optical sensor unit mounted on the exhaust stack and a remote readout and control unit connected to the sensor by cable. The essential elements of the sensor are (1) a small incandescent lamp (General Electric, No. 1630), mounted at one end of a collimating tube, which acts with a collimating lens as the light source, and (2) a selenium photovoltaic cell (Weston, model 836, type RRV) detector, mounted at the end of a receiving tube, which develops a photovoltage proportional to the light intensity incident on it. Figure 4 sketches the sensor unit mounted on an exhaust stack with the various parts identified. The remote readout and control unit performs a variety of functions:

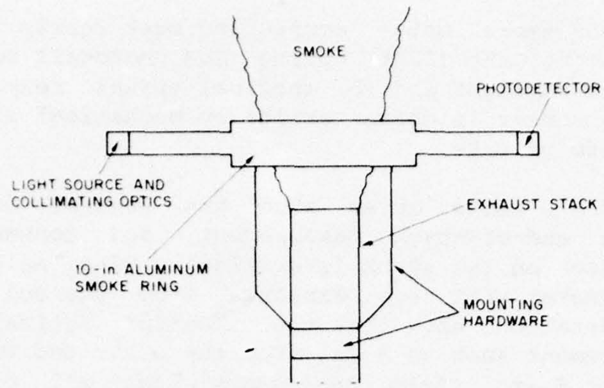

Figure 4. Sketch of USPHS smoke meter mounted on exhaust stack.

(a) It contains a microammeter (Simpson, model 1327T), calibrated in either percentage of opacity or transmittance, to read the photocell output.

(b) It routes purge air pressure to the sensor unit to aid in keeping the collimating lens and photocell free of soot deposits and regulates this pressure (external shop-air requirement is approximately 2 standard ft^3/min at 60 to 120 psi).

(c) It routes dc power to the sensor unit (external requirement is for a 2.75-A dc power supply furnishing a stable minimum of 6.5 V).

(d) For readout of the photocell output, it can accommodate a null-balance potentiometric-type, strip-chart recorder of 0 to 10 mV in lieu of the microammeter.

(e) It contains the instrument calibration adjustments.

The USPHS smoke meter has several important advantages. Owing to the very rapid response time of its optical system, the basic limitation on the instrument's capability for monitoring transient smoke levels lies in the response time of the readout system. With suitable recorders (light beam type or an oscilloscope), the smoke puffs from the individual cylinders of a multicylinder engine may be observed. A recorder with a 0.5-s full-scale response time, when used with this smoke meter, is considered adequate for measuring the transient smoke associated with federal engine certification.[11] To make the opacity

[11]*Federal Register*, 35, *No. 219 Part II (November 1970)*.

readings of the USPHS smoke meter correspond most nearly to the visual appearance of the smoke, the light source and photocell were chosen to approximate ordinary daylight and the spectral visual response of the human eye. The instrument is characterized by mechanical simplicity and is relatively easy to operate.

The USPHS smoke meter also has several disadvantages. Mainly, it is an end-of-stack measurement, and consequently, the location of the sensor on the stack is critical. Since an exhaust smoke plume varies in diameter with the distance from the end of the stack (gas dynamic considerations show that the inherent optical properties do, also), a measurement such as 4 in. from the stack end will not agree with a measurement 6 in. from the stack end, all else being the same.[12] This disagreement is partly due to path-length differences. This problem of different path lengths is a particular nuisance when the smoking of two stacks of different diameter is compared. It necessitates the calculation of the opacity difference due to the path length difference from the Beer-Lambert law (eq (1)) and its application to the data as a correction. End-of-stack measurements are also rather inconvenient for engine test laboratories where exhaust removal systems are centralized. These disadvantages are overcome with exhaust-sampling smoke meters or in-stack full-flow smoke meters, for which the path length is standardized. Another disadvantage of the USPHS smoke meter is that it is not self contained, but requires subsidiary facilities (electric power and shop air) that are not always available.

The USPHS smoke meter has been extensively used in a variety of situations. It is used by the Federal government to certify new diesel engines and is used often with a chassis dynamometer as a diagnostic tool for diesel vehicles. It is also well suited for use as a research tool in engine test cells, especially where transient smoke is of interest. It has not received much use as a roadside vehicle-check smoke meter, primarily because of the need for subsidiary equipment, or alternatively, complicated arrangements (such as the use of brake air and vehicle battery power). Its use as a garage maintenance tool by technically unsophisticated personnel also has been quite limited.

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[12] *R. C. Bascom, W. S. Chiu, and R. J. Padd, Measurement and Evaluation of Diesel Smoke, Paper 730212, Society of Automotive Engineers, International Automotive Engineering Congress, Detroit (January 1973).*

3.1.2 The B. P. Hartridge Smoke Meter

The B. P. Hartridge smoke meter (manufactured by Leslie Hartridge, Ltd.) has reached a high level of development and acceptance and occupies about the same position in the United Kingdom as the USPHS smoke meter does in the United States; that is, it is essentially the *British standard*. The Hartridge smoke meter is a sampling type of light-transmission instrument. It samples continuously by means of a probe installed either in the exhaust pipe close to the engine or in the open end of the stack. The instrument does not employ a vacuum pump; rather, a flow through the probe to the analyzer is induced either by normal back pressure in the exhaust system or by use of an impact probe (Pitot tube), which utilizes the dynamic head of the exhaust stream. A pressure relief valve, installed at the entrance to the smoke meter, maintains an essentially constant pressure within the instrument. Figure 5 diagrams the internal structure of the instrument. The heart of the analyzer is the pair of measuring tubes--a smoke tube and a clean-air reference tube. The smoke to be measured enters the smoke tube through the inlet marked A and exhausts out both ends. Air from a small blower continuously scavenges the clean-air tube and provides a curtain of air flow over the light source and photocell to keep them free of soot deposits. This air flow also purges the instrument case of smoke. Although at opposite ends of the measuring tubes, the light source and photocell are linked mechanically so that they can be moved

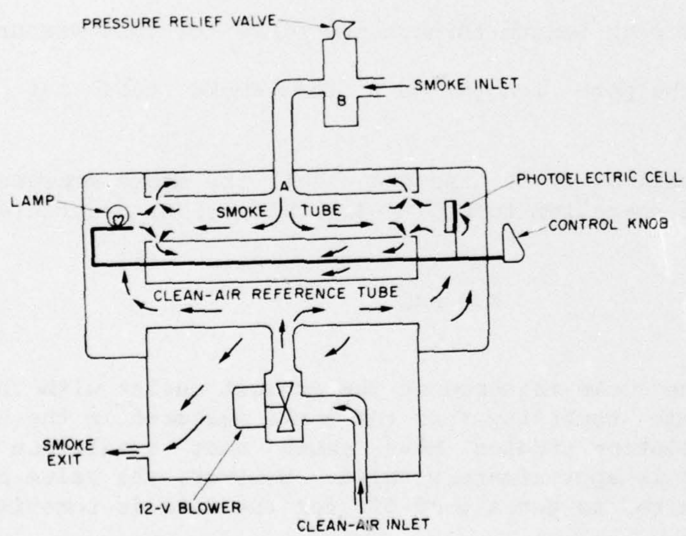

Figure 5. Internal configuration of B. P. Hartridge smoke meter (adapted from M. Vulliamy and J. Spiers, Paper 670090, SAE Automotive Engineering Congress Detroit (January 1967)).

together for scanning either the clean-air tube (for zero setting) or the smoke tube (for reading the smoke level). The output of the photocell (barrier-layer type) is read directly on a microammeter calibrated from 0 (the clean-air level) to 100 (completely opaque) Hartridge smoke units. The unit is battery powered.

As the main advantage, the smoke readings obtained with this intrument pertain to a sample of fixed path length and thus are not affected by exhaust-pipe diameter. Since the smoke-tube length is fixed and known, these readings can be related to smoke measurements made with other light-transmission smoke meters by the Beer-Lambert law. The equation that one predicts in this way for the USPHS smoke meter is, for example,

$$H = 100 \left[1 - \left(T_{PHS} \right)^{t_H/t_{PHS}} \right] , \tag{4}$$

where

H is the Hartridge smoke number,

T_{PHS} is the fractional transmittance of the smoke plume measured with the USPHS smoke meter

t_{PHS} is the path length through the plume for this measurement,

t_H is the path length down the smoke tube for the Hartridge measurement.

For this equation, it is assumed that the smoke measured in each case has the same so-called turbidity (or extinction) coefficient, K, where

$$K = n\bar{a}\bar{Q} \ . \tag{5}$$

That is, the smoke measured at the exhaust outlet with the USPHS meter has the same turbidity K as the smoke measured in the Hartridge smoke tube. Correlation studies have shown that a relation of the form of equation (4) is approximately valid. However, the value of the exponent t_H/t_{PHS} required to get a good fit for the data is sometimes higher than expected.[7]

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[7] *1967 CRC Diesel Smokemeter Calibration Tests, Coordinating Research Council Report No. 421 (June 1969).*

The basic problem in the use of the Hartridge smoke meter is to ensure, by an appropriate choice of sampling probe for the intended measurement, that a truly representative sample of smoke is delivered to the smoke tube. Sampling probes are not furnished with the instrument, and so the user must choose a sampling system in view of the gas dynamic conditions that exist at proposed sampling points in the exhaust system. If exhaust gas velocities are sufficiently high, such as when an engine is running at high speed, impact probes usually can deliver sufficient smoke to fill the smoke tube. However, with small engines running at low speed, this sampling method often fails to deliver enough smoke; low readings result. In general, the Hartridge smoke readings cannot be relied on if the pressure and temperature of the exhaust gas at the inlet to the smoke meter (fig. 5, point B) are not within the limits specified by the manufacturer. The temperature is important because the photocell is sensitive to temperature, and it is often necessary to cool the exhaust gas before letting it enter the smoke meter. The instrument also fails to give reliable readings if the pressure pulsations due to sequential cylinder firings are not sufficiently damped prior to entry into the smoke tube. This problem can usually be solved by probing the open end of the exhaust stack, rather than a point close to the engine. In general, the Hartridge smoke meter has been found to give reliable, repeatable results, provided sufficient care is taken in its use.

Although the Hartridge smoke meter has not had any widespread use in the United States, it has been used extensively in the United Kingdom. Its primary application has been in the engine test cell, where interest in transient smoke levels is not too high. The smoke meter has a borderline response time (it takes from 0.2 to 0.6 s to fill the smoke tube) in relation to transient smoke considerations. Some averaging is to be expected during rapidly changing engine conditions (accelerations), and thus smoke peaks during these periods are not detected accurately. The instrument has seen only limited use as a roadside vehicle-check smoke meter, primarily because of its bulk. It needs skilled attention to be operated properly and is not recommended for use by relatively untrained personnel.[13]

3.1.3 The Celesco In-Line Smoke Meter

Celesco Industries developed the in-line smoke meter in response to needs expressed by the Cummins Engine Co. It is intended for use only in engine test cells and chassis dynamometer test facilities. Its design has two innovations:

[13] *M. Vulliamy and J. Spiers, Diesel Engine Exhaust Smoke--Its Measurement, Regulation, and Control, Paper 670090, Society of Automotive Engineers Automotive Engineering Congress, Detroit (January 1967).*

(a) It measures the opacity of the full exhaust stream inside the exhaust line.

(b) The transmission measurement system is fully solid state, using a red light-emitting diode (LED) for the light source and a photodiode for the detector. It uses a pulsed-light technique that allows for essentially continuous referencing against the no-light condition.

The system consists of a sensor unit (fig. 6) installed in the exhaust line and a remote-control unit connected to the sensor by cable. The sensor is composed of two concentric steel cylindrical tubes, one of 6-in. o.d. and the other of 8-in. o.d. The inner tube has a 15-in. length, and the outer tube has a 13-in. length. The inner tube is flanged at its ends to allow mating with the incoming and outgoing sections of the exhaust line.

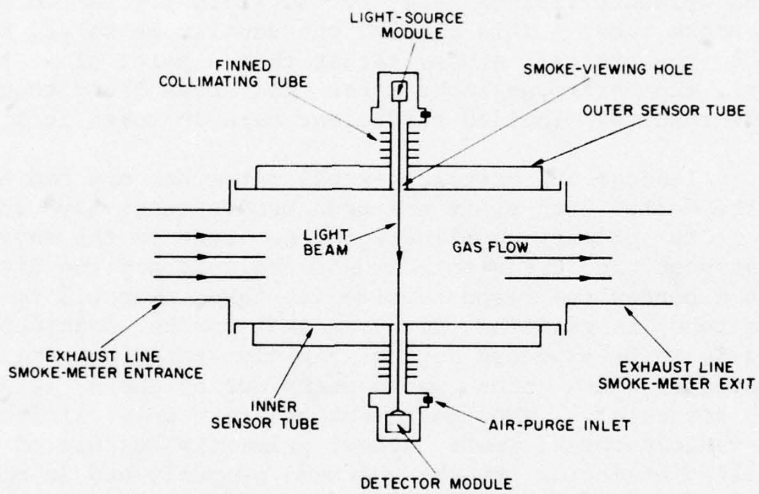

Figure 6. Cross-sectional schematic of Celesco in-line smoke meter (sensor unit).

The optical and electronic elements of the sensor (fig. 6) are in two phenolic modules that screw into a pair of finned (for thermal isolation) collimating tubes. These are in turn screwed into the outer cylinder of the sensor unit (at diametrically opposed points) so that their ends rest securely against a pair of smoke-viewing holes in the inner cylinder, thus forming a closed, leak-proof system. The sensor has an external compressed-air requirement (about 2.5 standard ft^3/min at 30 psi) to provide purge air for the collimating tubes. Part of this air is diverted into the space between the outer and inner cylinders for cooling. A solid-state LED, thermal compensator, and

collimating lens are mounted in one of the removable sensor modules, and a solid-state photodiode and signal preamplifier are mounted in the other. The ease with which these modules can be removed facilitates lens cleaning.

The remaining components of the system are in the remote-control unit. This has all the operating controls and a meter indicating percent opacity mounted on a standard rack panel 5-1/4 by 19 in. The major functional subassemblies of the chassis include the power supply, LED driving circuit, detector and meter circuit, and recorder amplifier circuit. The external electric-power requirement is for standard 115-V, 60-Hz line power.

The opacity is measured with this system as follows. The LED is mounted in the center of a flat-black background target that fills the detector's field of view. A unijunction oscillator drives the LED, which flashes on and off at about 4000 Hz. Thus, the photodetector (an extremely linear PIN silicon photodiode) alternately sees either no light or the light pulse from the LED (generally attenuated by the smoke). The photodiode response is preamplified (preamplifier in detector module) to obtain sufficient drive for the 50-ft interconnecting cable. The height of the pulses received at the control unit is proportional to the height of the light pulses received by the photodiode. The meter is set to zero by adjustment of the meter to read 0-percent opacity for the signal received with no smoke in the sensor. Circuitry is used to convert the height of the pulse train to a dc voltage level that is impressed across the meter circuit. The meter is set full scale by its adjustment to read 100-percent opacity when the light is off. This technique indicates the amount of smoke present that within limits, is, independent of soot deposits on the lenses, since the effect of soot deposits can be calibrated out by proper zero setting. The circuitry of this instrument is claimed to be extremely linear, so one would expect to get accurate results with proper zero and full-scale settings. The intermediate calibrations can always be checked, however, by use of Inconel neutral density filters calibrated at the wavelength of the LED (660 nm). The 0- to 95-percent response time of the instrument is 0.006 s. This is not the response time of the instrument panel meter, but that obtained by use of an oscilloscope for a readout device. So the instrument is quite suitable for transient smoke measurements.

The operating controls available on the instrument panel include 0- and 100-percent opacity adjustments, a hold-circuit switch to allow the operator to read peak opacity over a time interval, and a 0- to 20-percent meter-range switch for greater resolution in the lower opacity range. Accommodations are present also for readout of the opacity on a servo-type strip-chart recorder.

The advantages of this instrument are the direct result of the innovations in its design. The in-line sensor simultaneously overcomes the path length and gas dynamic vagaries associated with free plume smoke meters and also the sampling problems connected with the Hartridge smoke meter. Also, the scheme of the transmission measurement, although rather complex compared with that of the USPHS and Hartridge smoke meters, seems superior and less prone to error. General experience with the use of this smoke meter finds that it performs well, it is reliable, and its measurements are reproducible.

As the principal disadvantage of the in-line smoke meter, its use is restricted solely to the engine test cell and chassis dynamometer facility. Another difficulty is that its opacity readings fail to agree with those of the USPHS smoke meter (after Beer-Lambert normalization) and generally are lower.[12,14] The two apparent sources for this discrepancy are the spectral transmission properties of diesel smoke (the light sources of these instruments have different wavelength distributions) and the gas dynamic differences that exist between free plume and in-line smoke. In the visible region of the spectrum, diesel smoke is more transparent to longer wavelengths. Hence, the in-line smoke meter should read a lower opacity than the USPHS smoke meter. When corrections are made for the spectral effect, however, a discrepancy is still present: The in-line is still lower than the USPHS smoke meter, probably because of gas dynamic effects.

3.1.4 The Celesco Portable Smoke Meter

A simplification of Celesco's in-line smoke meter, the Celesco portable smoke meter is designed for end-of-stack measurements and portability. Its primary intended use is for quick checks of vehicle smoke, either at roadside or in a maintenance garage. It consists of an end-of-stack sensor unit and a small, hand-held indicator-and-control unit that contains the operating controls, meter, electrical circuitry, and power unit. Figure 7 shows the entire smoke meter.

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[12] *R. C. Bascom, W. S. Chiu, and R. J. Padd, Measurement and Evaluation of Diesel Smoke, Paper 730212, Society of Automotive Engineers, International Automotive Engineering Congress, Detroit (January 1973).*

[14] *J. O. Storment and K. J. Springer, Evaluation of Diesel Smoke Inspection Procedures and Smokemeters, Final Report Contract EHS 70-109, Southwest Research Institute Report No. AR-835 (July 1972).*

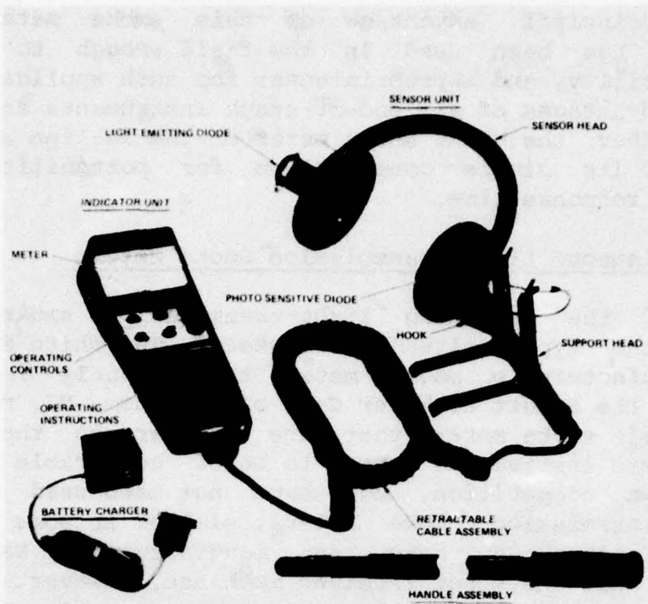

Figure 7. Parts of Celesco portable smoke meter.

The sensor unit comprises the light source and detector modules mounted in an easily removable manner on the sensor hardware assembly. The latter provides for easy mounting on the end of the exhaust stack, for proper alignment of the light source and detector (in a measurement the light passes through the center of the exhaust plume a few inches above the stack end), and for electrical connections to the modules. Also, a pair of baffle plates limits smoke deposits on the lenses. A retractable telephone cable connects the sensor to the indicator unit. This unit is powered by permanently installed rechargeable batteries. It has the following controls: (1) zero and full-scale adjustment, (2) zero- to 20-percent and zero- to 100-percent opacity ranges, (3) a hold-circuit control for reading peak opacity over some time interval, and (4) an on-off battery-charge switch (a battery charger is provided with the instrument). An output jack also is provided to allow operation of a strip-chart recorder.

The opacity measurement system is essentially the same as that used in the in-line smoke meter. The main differences are that (1) the LED flash frequency is approximately 300 Hz, (2) there is no preamplificaton provided in the detector module, and (3) the zero- to 100-percent opacity response time of the instrument is 0.2 s. The sensor unit has no provision for purge air to keep lenses free of soot deposits; however, the light source and detector modules are easily removed for cleaning. Also, thermal isolation of the sensor components is not as good as with the in-line smoke meter, primarily because of the lack of purge air.

The principal advantage of this smoke meter is its portability. It has been used in the field enough to prove its ruggedness, reliability, and appropriateness for such applications. But it shows the disadvantages of all end-of-stack instruments and is not as versatile as either the USPHS smoke meter or the in-line smoke meter, mainly because of its simple construction for portability and its relatively slower response time.

3.1.5 Miscellaneous Light-Transmission Smoke Meters

Most of the remaining light-transmission smoke meters are very similar to the types already discussed. The White Motor Co. of Torrence, CA, manufactures a smoke meter that closely resembles the USPHS instrument; the Robert H. Wager Co. of Chatham, NJ, manufactures in-line and portable smoke meters that are similar to their Celesco counterparts. These instruments appear to be of comparable quality to their better-known competition, but have not been used as widely. Portable light-transmission smoke meters, similar in some respects to the portable Celesco unit, have been manufactured by Bacharach and Nebetco. These units have not received much use, however. A portable light-transmission smoke meter developed in France by Union Technique de l'Automobile et du Cycle (UTAC) also is available in Europe. This instrument combines portability with a fixed-path-length (407-mm), end-of-stack opacity measurement. Detailed information on this instrument has not been received, however.

3.2 A Light-Scattering Smoke Meter

The Robert Bosch Corp. has developed a smoke measuring instrument, based on optical scattering from a smoke plume, that is referred to as the light-dispersion smoke meter. This instrument, like the Hartridge smoke meter, uses a probe inserted in the exhaust line to pick off a continuous, flowing exhaust sample for delivery to its detecting unit. Inside the detecting unit, the sampling line terminates in an open-ended nozzle to form a miniature exhaust stack of about 5/8-in. diameter. Figure 8 sketches the arrangements inside.[15] A light source and detecting photocell are positioned so that the photocell detects the light scattered from the sample plume 90 deg to the incident-beam direction. The photocell output is read directly on a meter or a strip-chart recorder calibrated in soot-weight density. As the main advantage of this smoke meter, besides that it analyzes a

[15] *Measuring Diesel Exhaust Smoke, Ethyl Technical Note, PCDTN 568, Ethyl Corp., Detroit (1968).*

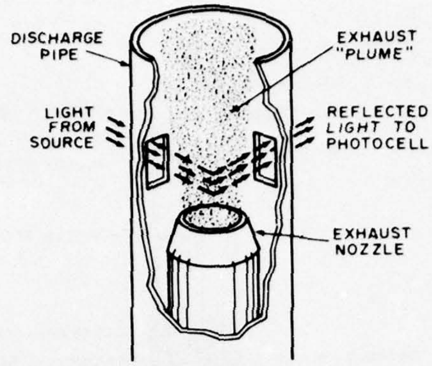

Figure 8. Internal configuration of Bosch light dispersion smoke meter (reproduced from Ethyl Technical Note, PCDTN 568, Ethyl Corp. (1968)).

standardized sample, its measurement correlates approximately linearly with soot-weight density over a range of smoke levels where most other instruments exhibit a logarithmic correlation. Unfortunately, only tentative evaluation data are available for the instrument at this time.

3.3 Smoke Meters Based on Filtering Techniques

3.3.1 The Robert Bosch Spot Smoke Meter

The most successful and best-known filter type of instrument in both the United States and Europe is the Robert Bosch spot smoke meter. The heart of the instrument is its single-shot sampling pump (fig. 9). Under normal use, the pump is clamped to the outside of the exhaust pipe at some point near the outlet and is connected with a short piece of tubing to a special sampling probe installed in the end of the exhaust stack. The sampling head of the pump has a removable filter holder, which houses the filter paper discs through which the exhaust sample is drawn. The sampling head is sealed against air leakage by "O" rings on each side of the filter holder. The pump is a spring-actuated piston type of unit with a synthetic rubber seal. The pump is cocked in preparation for sampling by depressing the piston to the bottom of its travel. It is held there by a ball detent until it is released for sampling by a tripping mechanism that can be remotely activated when a rubber bulb is squeezed. Spring pressure then forces the piston out, pulling a measured volume (330 cm^3) of exhaust gas through the filter paper. The resulting smoke spot deposited on the filter paper is then evaluated for degree of darkness by use of a photoelectric reflectometer supplied with the sampler. This unit (fig. 10) contains an incandescent light source, an annular photocell that detects the light reflected from

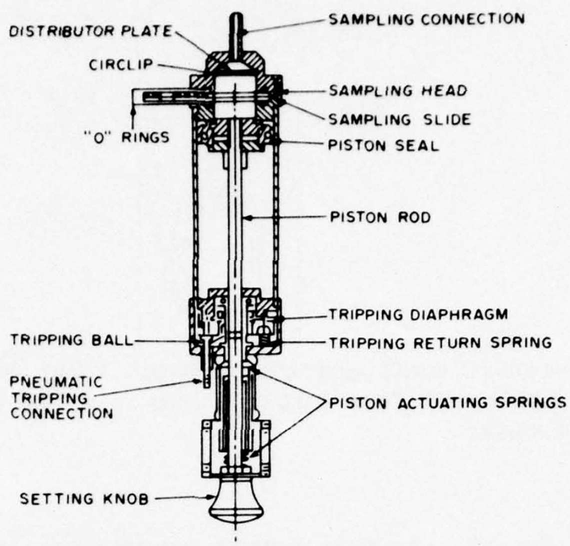

Figure 9. Bosch spot smoke meter sampling pump in cross section (reproduced from M. Vulliamy and J. Spiers, Paper 670090, SAE Automotive Engineering Congress (January 1967)).

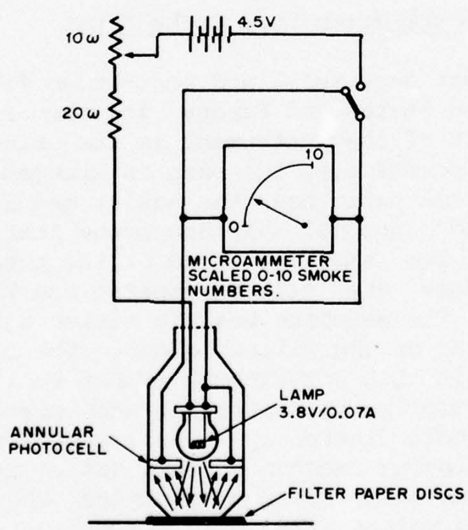

Figure 10. Bosch spot smoke meter photoelectric reflectometer unit (reproduced from M. Vulliamy and J. Spiers, 670090, SAE Automotive Engineering Congress (January 1967)).

the filter disc, and a microammeter that reads the photocell output in terms of Bosch smoke units (arbitrary units corresponding to the 0 to 10 scale of the meter). The unit is calibrated with a standard, perforated grid (supplied with the instrument), which corresponds to a Bosch reading of 5.0 units.

In the manufacture of this instrument, the sample volume, sample rate, and area of filter paper exposed to smoke are held to close tolerances. The filter paper also is made to close specifications. These all promote accuracy. The sources of error present in virtually all sampling systems (pulsations and large pressure variations in the exhaust system) continue to be present with this instrument, however. Gas leakage from the seals, as well as the presence of oil or unburnt fuel in the exhaust, also can lead to significant errors.

The instrument is patently unsuitable for transient smoke measurements. Nevertheless, the sampling time required to obtain a measurable amount of smoke (0.6 s) would not prevent making a single measurement during a variable smoke period, such as during engine acceleration. This short sampling time makes possible more elaborate spot smoke meters that take repeated samples at some rate in an attempt to record transient smoke.

The spot smoke meter has the advantages of genuine portability, ease of use, general ruggedness, and reliability. With proper use and maintenance, it can give reasonably accurate, reproducible results. The operation of the unit is easily understood, and with a standard and simple operating procedure laid down, relatively unskilled personnel can obtain good results. The primary disadvantage of the instrument is its inability to monitor transient smoke. This smoke meter has been used considerably in the engine test cell, where steady-state smoke is of primary interest. It has been accepted widely in Europe, especially in German-speaking and Scandinavian countries. In Sweden, this instrument is routinely used for roadside vehicle checks in the enforcement of smoke limits.

3.3.2 The Von Brand Continuous-Tape Smoke Meter

To overcome the major drawback of the Bosch spot smoke meter, the Von Brand continuous-tape instrument was developed. Figure 11 shows this filtering-sampler smoke meter. In operation, a small integrally mounted vacuum pump draws a continuous sample of gas through a moving filter tape that passes through the filter head of the instrument. A water separator in the sampling line and electric heating of the sample head are intended to limit moisture condensation on the filter tape.

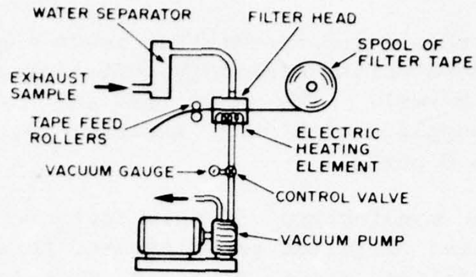

Figure 11. Von Brand continuous filtering smoke meter (reproduced from Ethyl Technical Note, PCDTN 568, Ethyl Corp. (1968)).

Tape speed is about 4 in./min, and the sampling vacuum is typically 2 to 5 in. of mercury. The continuous smoke record provided by the filter tape is evaluated for darkness of deposit by either visual comparison with a gray scale or by use of a light transmittance or reflective photometer similar to the Bosch evaluating unit.

This instrument, although probably the best known of its type, does not seem to be accepted widely, perhaps because of the frequent difficulties encountered with its use. There is difficulty in maintaining a constant pressure drop across the filter paper during transient engine operation. The surges in pressure in the sampling line during such conditions often lead to sample leakage at the filter head, thereby introducing sampling errors. It has also been demonstrated that the instrument is relatively insensitive to changes in smoke density at high smoke levels.[7]

4. SMOKE-METER CORRELATIONS AND MEASUREMENT PROBLEMS

This section mainly summarizes a number of recent, well-conducted correlation studies of diesel smoke meters. Also, the related questions of standards, smoke-meter accuracy, and general measurement problems are discussed. The most widely known and respected smoke-meter correlation studies performed in recent years were special subcommittee projects of the Coordinating Research Council (CRC), SAE, and Coordinating European Council (CEC). The on-going studies of the CEC have a wider scope than the others, in that various engine and vehicle smoke-inspection procedures and test methods also are being evaluated. Here, only the work concerned with the correlations of diesel smoke meters is summarized.

[7] *1967 CRC Diesel Smokemeter Calibration Tests, Coordinating Research Council Report No. 421 (June 1969).*

4.1 Coordinating Research Council Diesel-Smoke-Meter Correlations

The CRC Diesel Smokemeter Group correlated smoke meters in the fall of 1967 and reported on the correlations in the summer of 1969.[7] They evaluated seven smoke meters: Hartridge, USPHS, Beckman, Von Brand, Mobil continuous filtering, Bosch spot, and Bosch light dispersion, as well as the soot-concentration measurement techniques of the Caterpillar and the Ethyl Corp: (The Beckmann 912 smoke meter and the Mobile unit are no longer available commercially; the former was very much like the USPHS in overall design, and the latter was similar to the Von Brand unit.) Two trained Ringelmann raters also were included in the study. A widely used four-cycle truck engine and a two-cycle bus engine were used as smoke-generating sources. Two different fuels were used to represent the extremes marketed in terms of aromatic content and smoking tendency. Four different smoke levels were run (about 20, 40, 60, and 85 Hartridge units) with each engine and each fuel, while being measured with the instruments under evaluation. Every engine, fuel, and smoke-level combination was measured twice, but not consecutively. For data analysis, the Hartridge smoke meter was chosen as the reference meter (more or less arbitrarily and for lack of a real standard).

Four statistical analyses were performed on the data:

(a) A Yates Analysis was performed to determine the effect of engine and fuel on the smoke-meter reading. The Yates technique statistically analyzes the effect of varying several factors on the results of an experiment. A large effect was not found.

(b) Theoretical regression equations, based on the Beer-Lambert law, were developed to relate the Hartridge smoke numbers to the data from the three soot-concentration measurements (Bosch light dispersion, Caterpillar, and Ethyl Corp.). These equations were found to give a satisfactory estimate of the data.

(c) Semitheoretical regression equations were found necessary to obtain satisfactory estimates for the Hartridge versus the two opacity meters (USPHS and Beckman). These equations expressed the Beer-Lambert relationship among the meters, plus a constant.

(d) Empirical regression equations were developed to relate the filtering meters (Von Brand and Bosch spot) and the Ringelmann raters to the Hartridge smoke numbers.

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[7] *1967 CRC Diesel Smokemeter Calibration Tests, Coordinating Research Council Report No. 421 (June 1969).*

The results of the data-fitting analyses described in paragraphs (b) to (d) are shown in figure 12, which gives a nomograph, based on the chosen regression models, relating the readings of all the smoke meters tested. Table I gives a measure of the degree of correlation shown by the data or, alternatively, the error to be expected in use of the nomograph. This table lists, for each smoke meter tested, an unbiased estimate of error (expressed as a percentage of range in Hartridge smoke numbers) characterizing the regression equation relating that smoke meter to the Hartridge. It is essentially a measure of how well the regression equation fits the data.

A comparison of the CRC correlations with other published data indicated generally good agreement, except as follows:

(a) One of the Von Brand instruments gave rather high results compared to other data.

(b) The Bosch spot versus Hartridge correlation indicated that the Bosch readings were somewhat higher above 50 Hartridge smoke numbers than other published values.

(c) The Bosch light-dispersion-meter data were lower than published results.

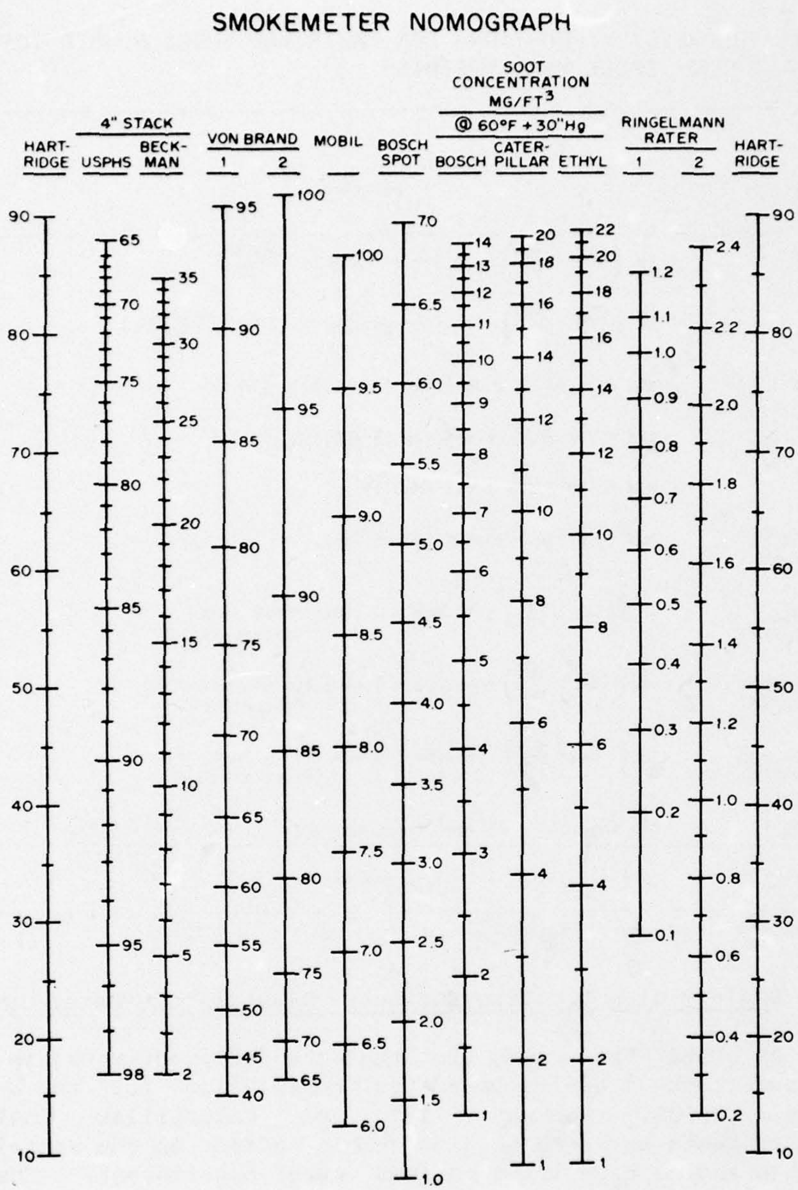

Figure 12. Smoke-meter correlations according to 1967 Coordinating Research Council smoke-meter-calibration study (reproduced from CRC Report No. 421 (June 1969)).

TABLE I. REGRESSION EQUATIONS FOR HARTRIDGE SMOKE NUMBER (HSN) VERSUS OTHER SMOKE MEASUREMENTS[1]

Meter	Equation	Unbiased estimate of error range, HSN
USPHS	$\ln\left(1.00 - \frac{HSN}{100}\right) = -0.099 + 4.538 \ln\left(\frac{USPHS}{100}\right)$	4.0
Beckman	$\ln\left(1.00 - \frac{HSN}{100}\right) = -0.106 + 4.124 \ln\left(1.00 - \frac{Beckman}{100}\right)$	4.2
Von Brand 1	$HSN = 11.681 - 0.0046\ (VB\ 1) + 0.0136\ (VB\ 1)^2$	15.0
Von Brand 2	$HSN = 201.797 - 6.098\ (VB\ 2) + 0.050\ (VB\ 2)^2$	5.8
Mobil	$HSN = -29.365 + 1.157\ (Mobil)^2$	6.7
Bosch Spot Concentration	$HSN = -5.736 + 13.579$ (Bosch Spot)	5.1
Bosch Soot Concentration	$\ln\left(1.00 - \frac{HSN}{100}\right) = +0.006 - 0.1502$ (Bosch Soot Concentration)	7.3
Caterpillar Soot Concentration	$\ln\left(1.00 - \frac{HSN}{100}\right) = +0.019 - 0.1103$ (Caterpillar Soot Concentration)	5.7
Ethyl Soot Concentration	$\ln\left(1.00 - \frac{HSN}{100}\right) = -0.004 - 0.100$ (Ethyl Soot Concentration)	5.1
Ringelmann 1	$HSN = 52.726 + 25.326$ (Ringelmann 1) $+ 11.447 \ln$ (Ringelmann 1)	11.4
Ringelmann 2	$HSN = 6.780 + 33.645$ (Ringelmann 2)	7.9

[1] *Adapted from Coordinating Research Council Report No. 421 (June 1969).*

4.2 Society of Automotive Engineers Diesel-Smoke-Meter Correlations

At about the same time that the CRC program was in progress, the SAE undertook diesel-smoke-meter correlation for the Bosch spot, Hartridge, USPHS, Beckman 912, and Caterpillar instruments.[5] Preliminary tests revealed no discernible effect on the correlations of varying the engine type (five engines were considered). These tests showed also that unless the smoke meters being correlated were read simultaneously, an undesirable degree of scatter would be present in the data. Accordingly, simultaneity was adopted.

[5] *A. W. Carey, Steady-State Correlation of Diesel Smoke Meters--An SAE Task Force Report, Paper 690492, Society of Automotive Engineers, Chicago (May 1969).*

The basic test plan was as follows. All meters were compared to the Bosch spot smoke meter. Four separate smoke levels were obtained by adjusting engine speed and dynamometer load. For each data run, simultaneous smoke-meter readings were taken with the Bosch spot and the smoke meter being correlated to it for each test smoke level. This procedure was repeated for all smoke meters in the test program. To determine the effect of exhaust stack diameter on the correlations, the entire correlation sequence was repeated for three exhaust stack diameters, 3, 4, and 6 in.

The results of these tests are summarized in figures 13 to 16. Figures 13 to 15 show, respectively, the correlations between the Bosch spot smoke meter and the opacimeters (USPHS and Beckman), the Hartridge meter, and the Caterpillar soot concentration measurement. A comparison of these results with the corresponding CRC correlations shows generally good agreement in the range below 5 Bosch units. Above this range, however, the CRC Bosch numbers are generally higher than the corresponding SAE results (by approximately 15 percent, at worst). The CRC has observed that its Bosch numbers were higher in the upper smoke range than those of other published studies (in particular, those of the Motor Industry Research Association[16] and the SAE results discussed here). Therefore, these CRC measurements were probably too high.

Figure 16 shows the results obtained for the opacimeter correlations when the stack diameter was varied. The effect shown is predicted quite accurately by the Beer-Lambert Law, as evidenced by the Beer-Lambert prediction points placed along the correlation curves for 3- and 6-in. stack diameters. (The curves in fig. 16 are fits of the experimental data.) These predictions are based on the observed opacity correlation obtained with the 4-in. diameter stack. The data can be used also to compare the Beer-Lambert predicted readings of the Hartridge smoke meter (18-in. path length) with those obtained experimentally. The prediction accuracy is excellent.

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[16] *A. E. Dodd and Z. Holubecki, The Measurement of Diesel Exhaust Smoke, Motor Industry Research Association, Report 1965/10, United Kingdom (1965).*

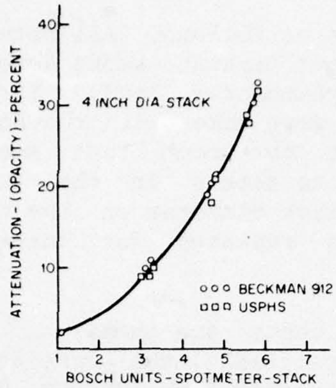

Figure 13. Correlation between opacimeters and Bosch spot smoke meter (reproduced from A. W. Carey, Paper 690492, SAE Mid-Year Meeting (May 1969)).

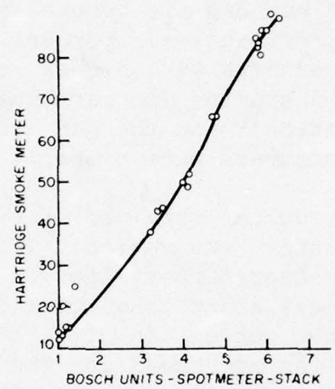

Figure 14. Correlation between Hartridge smoke meter and Bosch spot smoke meter (reproduced from A. W. Carey, Paper 690492, SAE Mid-Year Meeting (May 1969)).

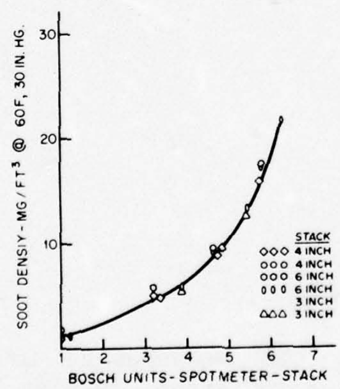

Figure 15. Correlation between Caterpillar soot concentration measurement and Bosch spot smoke meter (reproduced from A. W. Carey, Paper 690492, SAE Mid-Year Meeting (May 1969)).

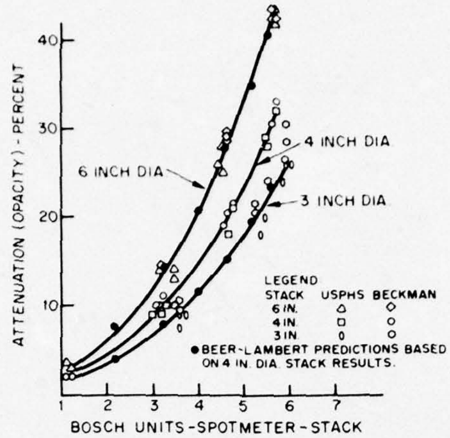

Figure 16. Correlations between opacimeters and Bosch spot smoke meter for stacks of various diameters, showing Beer-Lambert predictions for stacks of 3- and 6-in. diameters (reproduced from A. W. Carey, Paper 690492, SAE Mid-Year Meeting (May 1969)).

4.3 Coordinating European Council Diesel-Smoke-Meter Correlations

The Diesel Smoke Measurement Subcommittee of the CEC first met in November 1966. The investigations initiated by this committee and by some previously constituted national cooperative bodies were designed to assess the qualities of available smoke meters and the technical validity of various methods of using them. The results of these ongoing efforts have been admirably described by Pinolini and Spiers.[9] The following summary, which considers only the smoke-meter-correlation results, relies heavily on their reportage.

The Hartridge and Bosch spot smoke meters have been extensively correlated with measurements of soot concentration for a wide variety of diesel engines. The precision of the resulting calibrations is not high, primarily because of the variability of engines as smoke generators and because of the complex nature of such smoke. The large number of determinations that have been made, however, permits statistically significant mean calibration curves to be derived. These are shown in figure 17, where, in addition, similar calibration curves are furnished for the Bosch light dispersion and UTAC smoke meters. The latter were obtained by cross referencing smoke-meter data taken under standard conditions. In practice, the scatter of individual measured points can in all cases be as much as 20 percent. A comparison of these results with those of the SAE and CRC indicates generally good agreement.

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[9] *F. Pinolini and J. Spiers, Diesel Smoke--A Comparison of Test Methods and Smokemeters on Engine Test Bed and Vehicle, Paper 690491, Society of Automotive Engineers Mid-Year Meeting, Chicago (May 1969).*

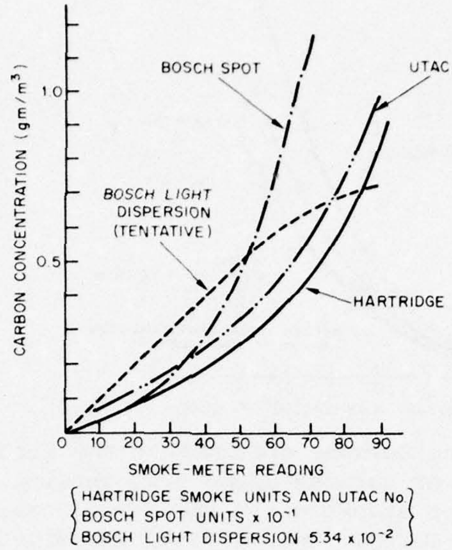

Figure 17. Mean smoke-meter calibration curves (adapted from F. Pinolini and J. Spiers, Paper 690491, SAE Mid-Year Meeting (May 1969)).

The USPHS smoke meter has been correlated with the Hartridge unit. Generally, the scatter of the experimental data about the mean correlation line is on the order of ±10 Hartridge numbers. It has, however, been shown that at low engine speeds, the USPHS meter can seriously underestimate the smoke density. The underestimation is thought to be due to the low velocity of exhaust-gas emission, which yields a smoke plume more easily dispersed by air currents. The experimental USPHS-Versus-Hartridge correlation has been found to agree well with that predicted by the Beer-Lambert law.

The smoke-meter measurements discussed here were made under full-load, steady-state engine conditions and apply to gray-black smoke only. Also, considerable skill and care were found necessary in the use of the various smoke meters, to obtain satisfactory repeatability.

4.4 Standards and Smoke-Meter Accuracy

The problem of standards for smoke-meter measurements is brought into sharp relief by the observation that in each of the three major correlation studies just discussed, a different standard of reference was used: the CRC designated the Hartridge meter as a standard, the SAE used the Bosch spot meter, and the CEC used soot concentration. Accuracy is determined by repeatedly measuring a standard whose value is already known, thereby evaluating the probable error involved in the use of the instrument. Alternatively, if such a

standard is not readily available, a surrogate standard in the form of an instrument of known accuracy can be used as a comparison. Unforturnately, for smoke-meter measurements, only surrogate standards of essentailly unknown accuracy are available.

There are basically two elements to this problem: (1) choosing a specific, inherent property of smoke to measure and (2) developing a method for producing standard smoke samples that exhibit this property in definite and graduated amounts. In connection with the first of these elements, the problem has been that several different properties were chosen (soot concentration, the opacity of smoke samples of different thicknesses, etc.). Two properties appear suitable--namely, the mass density of the aerosol particles that constitute the smoke and the optical extinction coefficient of the smoke (the factor $K = n\bar{a}\bar{Q}$ in the Beer-Lambert law). For this coefficient, since K depends on wavelength, a standard wavelength (or wavelength distribution) also must be chosen. Current standarization efforts appear to be moving along these lines. As the most probable result, in the future, smoke measurements will be stated in terms of either so called K-units or carbon-particle concentrations. Producing standard smoke is a much more difficult problem. It is only now being investigated at the National Bureau of Standards.

It is possible to estimate the accuracy with which various light-transmission smoke meters measure transmittance. The same can be said for the direct carbon-density measurements. In all of these cases, however, the smoke itself is questionable because of the sampling technique, plume turbulence, or other factors. In effect, all that can be done at this time is to evaluate the various smoke meters relative to each other. The reviewed correlation studies indicate that smoke-meter measurements are probably not much better than 5 percent and not much worse than 20 percent.

5. DIESEL-SMOKE-INSPECTION PROCEDURES

Smoke-inspection procedures evaluate the smoking tendencies of an engine class, an engine, or a vehicle; their purpose is engine certification, vehicle diagnostics, or smoke-limit enforcement. The many procedures range from the simple free acceleration tests to the complex engine-dynamometer driving schedule used for Federal diesel-engine certification. Their validity varies. This section describes the best known procedures and the results of recent evaluation studies that indicate when these procedures are appropriate.

5.1 Engine Certification

The procedure used by the Federal government for engine certification is as follows. This test is performed on an engine dynamometer by making smoke measurements with the USPHS smoke meter. The test begins after engine warm-up and a prescribed idle period (5 to 5.5 min) at the manufacturer's recommended low idle speed. First, engine speed is increased to 200 ± 50 rpm above idle speed within 3 s. The engine is then accelerated at full throttle, either against the inertia of the engine and dynamometer or against a preselected dynamometer load, so that it reaches 85 to 90 percent of rated speed in 5 ± 1.5 s. Then the engine speed is increased again from the speed of maximum rated torque or 60 percent of rated speed (whichever is higher), so that the engine speed reaches 95 to 100 percent of rated speed in 10 ± 2 s. This second acceleration is at full throttle against a preselected dynamometer load. Finally, a full-power lugdown from 95 to 100 percent of rated speed to the previous intermediate engine speed (peak torque speed or 60 percent of rated speed) is performed in 35 ± 5 s. This procedure is repeated three times. The smoke level is recorded continuously throughout this procedure, and the values of opacity at 1/2-s intervals during the two accelerations and the lugdown are entered on an evaluation sheet. The 15 highest values for the two accelerations are averaged, to obtain an opacity characterizing the engine's acceleration smoke. This average is referred to as the "a" factor. The five highest values for the lugdown mode are averaged to obtain the so-called "b" factor. The current legal limits are an "a" factor of no more than 40 percent and a "b" factor of no more than 20-percent opacity.[11]

This test can be performed also on a vehicle by adopting an appropriate procedure with a chassis dynamometer, such as the one developed at the Southwest Research Institute (SWRI).[14]

The European approach to prototype engine approval differs somewhat from the approach in the United States. The basic test in the United Kingdom is a series of constant full-load, steady-speed tests. This approach is evidently based on the beliefs that steady-state smoke measurements have greater reliability and on the fact that most European diesel vehicles are naturally aspirated. (Hence, acceleration-type tests are not as critical). These tests can be performed also on

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[11] *Federal Register, 35, No. 219, Part II (November 1970).*

[14] *J. O. Storment and K. J. Springer, Evaluation of Diesel Smoke Inspection Procedures and Smokemeters, Final Report Contract EHS 70-109, Southwest Research Institute Report No. AR-835 (July 1972).*

vehicles with a chassis dynamometer or on the road by braking the vehicle with a trailer type of dynamometer. The use of service brakes and road gradients also can approximate the conditions of these tests.

5.2 The New Jersey Smoke-Test Procedures

In New Jersey, two smoke tests are used to enforce smoke-control statutes.[17] One test, intended for trucks, is similar to the basic European procedure. With the chassis dynamometer, the truck is driven under no dynamometer load in a transmission gear that produces a maximum vehicle speed of 45 to 60 mph at governed engine rpm. Loading is then applied by power absorption, until engine rpm is reduced to 80 percent of the governed speed. This condition is maintained for 5 to 10 s; the peak smoke opacity during this period is taken as the test value. This opacity is not permitted to exceed 20 percent.

Without the chassis dynamometer, a gear ratio is selected to produce a maximum truck speed of 10 to 15 mph at governed rpm. The truck is driven in this manner, and the service brakes are applied, until the engine rpm is reduced to 80 percent of the governed rpm. The peak smoke opacity measured for 5 to 10 s of such brake loading is taken as the test value. The opacity may not exceed 20 percent.

The State of New Jersey also uses an acceleration test, but this is intended solely for buses. This test, done on the road, involves a full-throttle acceleration from rest to a bus speed of 20 mph. This is intended to simulate a bus pulling away from the curb. The peak smoke opacity measured during this acceleration (approximately 8 to 12 s in duration) is not permitted to exceed 40 percent.

For the New Jersey tests, the Celesco portable smoke meter is used, and the Wager portable smoke meter has been approved.

5.3 Miscellaneous Smoke-Test Procedures

The simplest of smoke-test procedures is the so-called free-acceleration test. This test is intended for vehicles, and its principal attraction is the ease with which it can be performed. With the vehicle at rest and the transmission in neutral, the engine is given a full-throttle acceleration from about 1000 to 1200 rpm to maximum governed engine speed. When the maximum speed is reached, the throttle is partly closed, and engine speed is allowed to drop back to 1000 to 1200 rpm. This test is repeated several times until three or four repeatable peak-opacity readings are obtained. This repeatable opacity reading is taken as test the value.

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[17]*New Jersey Department of Environmental Protection, Air Pollution Control Code.*

A simplified chassis-dynamometer-test procedure developed by SWRI combines an acceleration mode and a steady-state mode.[14] As an advantage, it can be performed with only one preset dynamometer load. The load is determined by driving the vehicle at rated-speed and full-power output in a transmission gear that produces a rear wheel speed of 45 to 65 mph. With this load set in the power-absorption unit and the vehicle at low idle speed (rear wheels stationary), the vehicle clutch is engaged in a smooth, steady manner, and a full-throttle acceleration is begun. Engine speed increases quite rapidly at first, due to the absence of any inertia simulation flywheels on the dynamometer rolls. However, as rear wheel speed increases, the load stored in the power-absorption unit becomes effective, and engine speed increases at a slower rate. Within 5 to 10 s after the start of the acceleration, the engine reaches its rated speed. This maximum power condition at rated speed is maintained for approximately 10 s. Smoke opacity is recorded during the acceleration and maximum power condition, and the resulting recorder trace is analyzed to obtain both peak and average opacity.

5.4 Evaluations of Smoke-Test Procedures

The most thorough study of the validity of various smoke-test procedures that is available in the literature has been summarized by Pinolini and Spiers.[9] The work itself was part of the overall project of the CEC Diesel Smoke Measurement Subcommittee. A study at SWRI in 1971-72 was concerned, in part, with the evaluation of smoke-test procedures.[14]

5.4.1 The Coordinating European Council Study

Three smoke-test procedures were evaluated by the CEC: (1) full-load, constant-speed tests, performed on a chassis dynamometer, with a trailer type of dynamometer, or by simulation on the road with service brakes and road gradients; (2) controlled acceleration tests, wherein the engine is operated at full load under various controlled rates of acceleration; and (3) free-acceleration tests. Most engines tested were of the four-stroke, naturally aspirated type. The program tested 60 representative diesel engines from France, Germany, Holland, Italy, Sweden, Switzerland, and the United Kingdom. Of them, 51 were of

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[9] *F. Pinolini and J. Spiers, Diesel Smoke--A Comparison of Test Methods and Smokemeters on Engine Test Bed and Vehicle, Paper 690491, Society of Automotive Engineers Mid-Year Meeting, Chicago (May 1969).*

[14] *J. O. Storment and K. J. Springer, Evaluation of Diesel Smoke Inspection Procedures and Smokemeters, Final Report Contract EHS 70-109, Southwest Research Institute Report No. AR-835 (July 1972).*

the four-stroke, naturally aspirated type; 8 were four-stroke supercharged; and 1 was two-stroke turbocharged. Fully laden vehicle weight ranged from 1.3 to 32 tons; the total engine displacement ranged from 1.255 to 12.8 liters; and the maximum power output ranged from 40.6 hp at 4000 rpm to 298 hp at 2200 rpm. Smoke was measured with the Hartridge smoke meter.

The full-load, constant-speed tests were done at a number of different engine speeds, from about 35 percent of rated speed to rated speed. The results were practically the same, whether the engines were tested on engine dynamometers or via the various vehicle simulations (full-load, constant-speed tests on an engine dynamometer are normally used by manufacturers for the development of their engines). Smoke production was generally highest at the lower engine speeds.

The maximum smoke levels obtained during the controlled-acceleration tests generally agreed with those of the full-load, constant-speed tests, provided that the controlled accelerations were sufficiently slow (that is, of duration greater than 15 s). In fact, a trend to higher smoke readings with decreasing acceleration rates was observed for the naturally aspirated engines.

The free-acceleration tests generally gave the lowest peak smoke levels for the naturally aspirated engines and the highest smoke levels for the supercharged engines fitted with an exhaust driven turboblower. Also, the correlation between free acceleration peak smoke levels and maximum steady-state smoke levels was unsatisfactory for ranking the engines by greatest smoke production. The ordering differed using steady-state smoke and free-accelerations smoke levels as criteria.

The main conclusions of this study were as follows:

(a) For full-load, constant-speed tests, smoke measurements are independent of engine inertial and exhaust system effects and generally give the highest smoke density that is likely to be emitted by the vehicles in normal use.

(b) For these test conditions, it is relatively unimportant whether the engine is on the test bed or in the vehicle or whether it is braked by a chassis dynamometer or controlled on the road by the vehicle brakes.

(c) Smoke density read during controlled acceleration tests depends on the engine inertial and exhaust systems. Although the maximum readings obtained in this way agree reasonably well with the steady-state maxima, using these more complicated tests is not advantageous.

(d) The results obtained with the free-acceleration tests indicate that they should be excluded from the group of technically sound test methods.

5.4.2 The Southwest Research Institute Study

In the SWRI study, four smoke-test procedures were compared with a chassis-dynamometer simulation of the Federal certification test. The tests evaluated included the two New Jersey smoke tests (chassis dynamometer versions), the free-acceleration test, and the SWRI's simplified chassis dynamometer procedure. Four truck-tractors and one bus were used as the test vehicles. The truck engines--two naturally aspirated Cummins NHC-250's, a turbocharged Cummins NTC-335, and a naturally aspirated Caterpillar 1150--were chosen to provide a wide range of smoke opacities and exhaust flow rates. Additional consideration was given to such engine operating characteristics as whether smoke output is highest during acceleration or lugdown and whether acceleration smoke peaks are of long or short duration. One of the NHC-250 engines had a restrictor plate installed in the intake manifold, to increase its smoking tendency. The bus was powered with a Detroit Diesel 6V-71 two-cycle engine, common to most municipal buses. All smoke was measured with a USPHS smoke meter.

The truck-tractor tests resulted as follows:

(a) Reasonably good correlation was obtained between the Federal "b" factors and the New Jersey and SWRI steady-state test modes.

(b) Correlation was poor between the Federal "a" factors and the acceleration modes of the SWRI test.

(c) Peak-acceleration smoke levels during the Federal and SWRI cycles correlated fairly well.

(d) Generally, the free-acceleration smoke levels did not correlate well with any aspect of the Federal test. An exception to this was a rather accurate duplication of the Federal "a" factors, provided that the turbocharged engine data were omitted.

The bus tests resulted as follows:

(a) The acceleration and steady-state modes of the SWRI test correlated well, respectively, with the "a" and "b" factors of the Federal test.

(b) The New Jersey bus-acceleration peaks correlated fairly well with the Federal "a" factors and acceleration peaks and to a lesser degree with the free-acceleration smoke peaks.

The scope of the SWRI smoke test study was, unfortunately, not as great as that of the CEC. It is, in fact, difficult to attribute a great deal of statistical significance to the SWRI results, because the quantity of data does not merit it. With this qualification, the results of the study suggest that (1) a simpler chassis dynamometer procedure (the SWRI's) may be substituted for the Federal test under certain conditions; (2) the New Jersey tests seem appropriate as vehicle inspection tests, especially as they appear directly related to regular in-service operation of the vehicles; and (3) the free-acceleration test has dubious merit.

5.4.3 Smoke-Test Procedures in General

The aim of a smoke test is generally either (1) to survey the smoking tendency of a broad class of diesel engines or vehicles or (2) to establish that a particular vehicle either performs acceptably or needs repair. Since the smoking character of diesel engines and vehicles varies widely, no single smoke test can accommodate all of these alternative aims unless it is exceedingly complex. In general, a less-than-perfect test has to be used for expediency, mainly because diesel engines and vehicles vary widely, and the consequent variety in smoking character has to be dealt with.

The results of these studies suggest that, for maintenance, the New Jersey steady-state truck-smoke test is probably the best compromise between technical validity and simplicity. The version of this test that is performed on the road with the aid of the vehicle service brakes has the additional simplifying feature of requiring no special equipment other than a smoke meter. However, a compromise of this sort may not be necessary if the fleet uses only a few different diesel engines. The smoking character of a group of typical vehicles could be studied and thoroughly documented, as in the CEC study, and a smoke test attuned to typical vehicle behavior could be developed on this basis.

6. EXISTING SMOKE-CONTROL PROGRAMS

Smoke-control programs arise from two distinct areas of interest: the enforcement of air-quality-related legislation and diesel-vehicle maintenance. Enforcement programs exist at both the Federal and State levels and complement one another. Smoke control maintenance programs by fleet owners in the United States have appeared slowly and have developed most in areas where smoke-limit enforcement is pursued with vigor.

6.1 Enforcement Programs

6.1.1 Federal Programs

At the level of certification, Federal law requires that diesel engines for vehicles in excess of 6000 lb gross vehicle weight (GVW), manufacturered for use in 1970 and thereafter, must be submitted for certification by the Federal smoke-compliance test. Certification test samples consisting of typical-production engines are sufficient. This test consists of the Federal smoke test, on an engine dynamometer, with 40- and 20-percent-opacity limits for the "a" and "b" factors, respectively.[11] These tests are performed at the Environmental Protection Agency's engine test facility at Ann Arbor, MI.

Frankly admitted by EPA officials, the major goal of these compliance tests is to encourage engine manufacturers to lower the smoke output of their engines through attention to relatively simple design considerations, such as engine rating. The Federal acceptance levels were set not with criteria of public acceptability in mind, but rather to be easily met with relatively small investments in design effort. This goal has been achieved. Post-1970 diesel-powered vehicles generally smoke less than pre-1970 vehicles, and almost none of the former has difficulty with certification.

6.1.2 New Jersey Programs

It is left to the individual states to formulate and enforce smoke-control regulations that apply to on-road diesel vehicles. New Jersey is located on the heaviest truck route in the United States and was therefore among the first states to devise and institute a smoke-control system of wide scope. Four different standards and test procedures have been used in this system, of which two remain. A no-visible-smoke standard, requiring that no diesel vehicle emit visible smoke for longer than 5 s while in operation on public highways, was recently rejected by the New Jersey courts. A free-acceleration test, which was given considerable attention for its operational simplicity, was eventually dropped for lack of technical validity. What remains are the two New Jersey smoke tests, one for trucks and one for buses, and the system of regulations that apply them to smoke-limit enforcement.

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[11] *Federal Register*, 35, No. 219, Part II (November 1970).

The bus regulations are as follows:

(a) Every bus operated in New Jersey that is subject to inspection by the Public Utilities Commission (PUC) (virtually all intrastate buses) must be subjected to the bus-acceleration smoke test with the approved smoke meter, as part of its biannual maintenance inspection. Failure to meet the 40-percent-opacity limit prescribed by this test renders the bus out of service until repaired to correct the smoking condition. As a practical matter, this inspection system has effectively controlled bus smoke. Most buses exhibit acceleration smoke levels well below the 40-percent-opacity limit after their biannual maintenance.

(b) The time interval between maintenance inspections and the interstate bus traffic not included under (a) is covered by a regulation making it a misdemeanor to operate a noncomplying bus on the public highways. In practice, buses that appear to be smoking excessively can be given the smoke test by a PUC inspector and cited if found in violation.

(c) Any person restoring a bus to service that has been ordered out of service by the PUC is deemed disorderly.

The overall success with bus smoke control contrasts sharply with the relative ineffectiveness of the *New Jersey truck-smoke program*, mainly because the courts rejected the no-visible-smoke regulation and fleet owners did not cooperate. The system governing the use of the New Jersey truck-smoke test is as follows:

(a) Virtually all diesel-powered trucks in excess of 6,000 lb GVW garaged in New Jersey are subject to inspection by the Division of Motor Vehicles (DMV) every 3 months. This inspection consists of the New Jersey truck-smoke test, using the approved smoke meter, with a 20-percent-opacity limit prescribed for acceptance. Since it is impractical for the DMV to inspect all of the trucks as required, a self-inspection provision has been included. When the self-inspection privilege is granted, the owner must inspect his fleet every 3 months.

(b) Violations of the 20-percent-opacity standard or of the provisions of the self-inspection procedure may be penalized by suspension or revocation of New Jersey registration and license privileges, loss of the self-inspection privilege, or both.

The regulation that had been intended to complete this enforcement procedure was the no-visible-smoke regulation, violation of which carried a fine from $25 to $100. The legal rejection of this

regulation, the DMV's incapacity for inspecting all of the trucks itself, and the general lack of fleet owner cooperation have rendered this system ineffective. New Jersey is exploring other alternatives.

6.1.3 California Programs

California has long been regarded as a leader in statewide air-quality legislation and programs. The approach to smoke control adopted there differs in several important respects from that of New Jersey. California did not emphasize developing smoke-inspection procedures with a high degree of technical validity and reliability. The Ringelmann chart was adopted as a standard, and the Ringelmann method was adopted for evaluation. Rather, California has mainly emphasized the development and implementation of tough, enforceable smoke-limit statutes.

The most effective regulation is in the California Health and Safety Code, which forbids Ringelmann 2 smoke (nominally 40-percent opacity) or greater for a period of 3 min or more (not necessarily consecutive). The effectiveness of this regulation is due mainly to its provision of severe penalties: the fine can be as much as $500, court appearance is mandatory (fees paid by the violator), and that needed repairs have been made must be proved. This regulation is enforced by the California Air Pollution Control Districts, which were specially formed to deal strictly with air-quality matters where air-pollution problems are acute, like in Los Angeles County. There is seldom any difficulty in obtaining court convictions in these cases, since highly trained Ringelmann raters, recognized by the courts as experts, generally issue the citations. This enforcement and the severity of the penalties have resulted in a high degree of fleet-owner cooperation.

The Health and Safety Code regulation, which is aimed mainly at gross offenders, is supplemented by a State Motor Vehicle Code regulation. This distinguishes pre-1971 from later-model diesel vehicles: pre-1971 vehicles may not emit Ringelmann 2 smoke or greater for more than 10 s; for later-modeled vehicles, the limit is Ringelmann 1. This regulation pertains only at elevations of less than 4000 ft. It is enforced by both the California Highway Patrol (using pocket-sized Ringelmann charts) and the Air Pollution Control Districts. The fine is only $15.

The California program has generally been quite effective. Unlike the New Jersey program, it has not directly contributed to smoke-control maintenance by furnishing instruments and inspection procedures. Nevertheless, it has shown an effective way of limiting on-road diesel smoke: a no-nonsense approach to enforcement based solidly on legality.

6.1.4 Other States

Many other states and municipalities are considering or enforcing smoke-limit regulations for on-road diesel vehicles. Most of these are following the example of California, such as New York State and St. Louis County. In New York, regulations covering all diesel vehicles (except marine) operating in the State were adopted in 1968. The standard permits up to 20-percent opacity for normal running and smoke puffs above 20-percent opacity during acceleration if they last no longer than 5 s. Inspectors trained in visual methods enforce the regulations.

St. Louis County uses No. 2 Ringelmann as its basic standard. Smoke in excess of this is permitted, provided that it lasts for no more than 100 yd of vehicle travel. Enforcement is by police trained in visual methods based on the use of a smoke generator.

Moreover, New Hampshire is considering a smoke-control program whose standard will be based on portable smoke-meter measurements. New Hampshire is currently evaluating the Celesco portable smoke meter for this purpose.

6.2 Maintenance Programs

Commercial fleet maintenance programs to control smoke have appeared in proportion to the vigor of smoke-limit enforcement by local authorities and the severity of the penalties carried by smoke citations. Little cooperation by commercial truckers has been evident in New Jersey, owing to the legal impotence of that State's system. In contrast, a fair degree of concern with smoke has manifested itself in California, particularly among trucking outfits operating near or in Los Angeles.

Where they exist, smoke-control maintenance programs generally take one of two extreme forms: (1) In informal programs, fuel and air induction systems are maintained for vehicles that appear to smoke too much. (2) In fairly elaborate programs, a smoke meter is used with a chassis dynamometer to verify or suggest repairs. In form (1), no instruments are used to gauge smoke production; the eye and judgment of maintenance mechanics and rig operators are deemed sufficient. In form (2), the chassis dynamometer procedure usually is a simulation of that in the Federal certification test. Two examples illustrate the general situation.

In 1972, an Azusa-based trucking company, Consolidated Rock (Conrock), which does a considerable cement and sand hauling business in Los Angeles, became seriously interested in smoke-control maintenance. This interest was largely in response to the great number of smoke citations that its rigs were getting from the Los Angeles County Air Pollution Control District. Conrock, the Clayton Dynamometer Co., and the White Motor Co. set up a maintenance program for smoke reduction. A chassis-dynamometer smoke-test procedure developed by Clayton (similar to the SWRI simulation of the Federal certification procedure) was used with the White smoke meter (very similar to the USPHS) to test and verify the reduction of smoking. Concurrent with this maintenance program, Conrock's rigs, which mainly use the Cummins 180 engine, were being retrofitted with an ecology kit designed by the Cummins Engine Company for a wide category of its engines. This kit provides a turbocharging modification for cruise smoke reduction and an aneroid-valve control mechanism to limit acceleration smoke. The program succeeded well. The smoke was reduced as desired and the smoke citations abated.

Cummins has been interested in smoke measurement and control for quite some time, mostly because Cummins and several other engine manufacturers produce a number of diesel engines that have smoke problems. Also, Cummins has been anticipating tougher smoke regulations from both Federal and State authorities. Unlike many other diesel engine manufacturers, Cummins controls the distribution and sale of many of the rigs with its engines and, consequently, gets a good deal of feedback from purchasers through its service operation. Cummins has therefore prepared itself to provide good-quality smoke-control maintenance as part of its distributor's service operation. Many of these distributors have been equipped with the portable Celesco smoke meter and have chassis-dynamometer facilities for diagnostics. The intention is to provide smoke maintenance through use of the smoke meter and a chassis dynamometer simulation of the Federal smoke-test procedure. However, since most anticipated tougher regulations have not yet materialized, these intentions are not being carried out to any great degree.

7. THE DIESEL-SMOKE PROBLEM OF THE MILITARY FLEET

This section describes the specifics of the diesel-smoke problem for Army vehicles. It summarizes the information in relevant test reports, as well as the results of a number of interviews with experts. It is hoped that, in this way, the basic aspects of the problem will emerge clearly for intelligent consideration of the alternative solutions possible.

7.1 Military Cargo-Truck Smoke-Test Reports

Only two published studies (SWRI) appear to have included the generation of test data on the smoking characteristics of military diesel vehicles. Both studies concentrated on the 2-1/2- and 5-ton cargo trucks powered by the LD 465 and LDS 465 engines. Although neither of these studies generated enough test data to permit statistical conclusions to be drawn, the multifuel 465 engine powers about 70 percent of the military fleet, so these data are of considerable interest.

In the first SWRI study (late 1960's), the base-line power output, smoke, and exhaust emissions were measured during a 20,000-mile lubrication oil fleet test.[18] The test fleet consisted of four M54A2 5-ton cargo trucks powered by the LDS 465 compression ignition engine. Two of the vehicles were operated with a MIL-L-2104B and two with a series-3 crankcase lubricant. Smoke was tested on two of the vehicles (both lubricants were represented) at intervals of 50, 6,500, 12,000, and 19,500 miles. Smoke was tested on the other two trucks at the beginning, 12,000-mile point, and end of the fleet test. The tests used a chassis dynamometer and were of two types: (1) constant-speed, full-power tests at various engine speeds, from idle to rated, and (2) transient-speed tests consisting of engine start up and full-rack accelerations against a 32,000-lb inertia equivalent and road load, in each forward gear. Smoke was measured with a USPHS smoke meter; in addition, smoke under constant speed was measured with a Bosch spot smoke meter.

Table II gives the results of the constant-speed, full-power tests. Three features of these results bear emphasis: (1) the idle smoke levels are much higher than those typically obtained from commercial diesel vehicles, whether naturally aspirated or turbocharged; (2) smoke levels tend to increase as engine speed is decreased (this is typical of turbocharged vehicles), with a maximum at about 1800 rpm; (3) smoke levels tend to increase with accumulated mileage (typical of commercial rigs) up to about 12,000 miles, thereafter either remaining the same or decreasing. The smoke levels shown in table II can be placed in perspective to some degree by being compared to the results of similar constant-speed tests on a broad spectrum of European vehicles (such as in the CEC tests, sect. 5.4.1). Such a comparison places these LDS 465 engine results among those of the heavier-smoking European vehicles. Comparable constant-speed test results for typical vehicles in the United States are not available in the literature.

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[18] *K. J. Springer, Baseline Exhaust Emissions from U.S. Army M54A2 LDS 465 Powered Five-Ton Trucks, Final Report Contract No. DAAD05-67-C-0361, Southwest Research Institute Report No. AR-690 (April 1969).*

TABLE II. STEADY-SPEED, FULL-LOAD SMOKE-TEST RESULTS ON FOUR U.S. ARMY M54A2 LDS 465 POWERED 5-TON TRUCKS[1,2]

Miles	50				6,500				12,000				19,500			
Truck No.	Smoke at rpm				Smoke at rpm				Smoke at rpm				Smoke at rpm			
	2600	2200	1800	Idle	2600	2200	1800	Idle	2600	2200	1800	Idle	2600	2200	1800	Idle
5D5809	5	6	25	5	3	10	26	5	7	12	35	6	6	10	44	5
5E5774	7	14	29	22	6	16	30	8	7	13	45	9	6	7	29	8
5E5775	8	13	23	16	-	-	-	-	13	16	42	4	12	8	29	4
5E5776	10	15	23	11	-	-	-	-	10	16	37	11	11	14	20	16

[1] *Reproduced from K. J. Springer, Southwest Research Institute Report No. AR-690 (April 1969).*
[2] *Smoke readings are in percent opacity as measured with USPHS smoke meter.*

The results of the transient-speed tests are shown in table III. The smoke readings given are the peak values observed averaged over a number of repeated tests. The smoke levels for a given test condition tend to remain about the same as engine mileage accumulates. The smoke levels produced in the higher gears are generally less than those produced in the lower gear accelerations. The greatest variation continues to be manifest in the idle condition. It is observed in the test report that smoke levels for these tests are high compared to those of previously performed identical tests on commercial truck-tractors using a No. 2 diesel fuel.

TABLE III. TRANSIENT-SPEED SMOKE-TEST RESULTS ON FOUR U.S. ARMY M54A2 LDS 465 POWERED 5-TON TRUCKS[1]

Truck No.	Test miles	USPHS smoke meter readings, % opacity						
		Engine start	3-min idle	First gear	Second gear	Third gear	Fourth gear	Fifth gear
5D5809	50	62	8	93	81	78	75	60
	6,500	56	5	92	82	78	83	69
	12,000	59	6	91	83	77	80	65
	19,500	45	5	89	68	71	73	58
5E5774	50	66	21	92	79	75	74	69
	6,500	47	9	71	78	77	77	63
	12,000	60	9	82	75	74	73	64
	19,500	65	8	92	76	76	76	62
5E5775	50	61	17	97	84	74	74	63
	12,000	59	4	92	92	88	88	85
	19,500	48	4	90	77	75	74	60
5E5776	50	56	11	92	68	61	67	52
	12,000	54	11	85	71	69	71	50
	19,500	55	18	85	69	61	64	48

[1] *Reproduced from K. J. Springer, Southwest Research Institute Report No. AR-690 (April 1969).*

During this test program, the effect of a commercial (barium based) smoke-supressant fuel additive was briefly investigated. It was found to reduce the smoke level fairly consistently during the constant speed tests by about 50 percent. However, under transient speed conditions, it was found to be mostly ineffective.

The second SWRI study, reported in May 1971, included smoke tests of three 2-1/2-ton military cargo trucks in use and powered by LD 465 engines and three 5-ton cargo trucks in use and powered by LDS 465 engines.[19] The trucks exhibited various odometer miles (from about 3,000 to 20,000 miles) and were tested in their received condition. The smoke tests included constant-speed, full-power tests at various engine speeds and the Federal certification smoke test (chassis-dynamometer simulation). The USPHS smoke meter was used for all smoke measurements.

Table IV summarizes the results obtained with the Federal smoke compliance test. Only one of the three LDS 465 powered trucks would have passed the Federal test. Trucks No. 1 and 3 would have failed the 40-percent "a"-factor limit by a considerable margin, and although they met the "b"-factor limit of 20 percent, they did so only marginally. Concerning the high "a" factors for these two trucks, the test report says that these figures represent "a gross amount of smoke that has rarely been equaled by previously tested uncontrolled diesel engines."[19] Also, truck No. 2 was atypical: it consistently delivered

TABLE IV. FEDERAL CERTIFICATION TEST DATA ON THREE IN-USE LDS 465 POWERED 5-TON AND THREE IN-USE LD 465 POWERED 2-1/2-TON MILITARY CARGO TRUCKS.[1]

Truck No.	Mileage	"a" Factor	"b" Factor
	LDS 465		
(1)	2084	50.2	13.4
(2)	4762	25.2	6.5
(3)	8799	66.9	19.8
	LD 465		
(4)	3733	40.8	41.4
(5)	11,551	15.9	9.4
(6)	21,472	36.3	38.5

[1] *Adapted from K. J. Springer, Southwest Research Institute Report No. AR-805 (May 1971).*

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[19] *K. J. Springer, Preliminary Survey of In-Use Army Vehicle Emissions Characteristics, Final Report Contract No. DAAD05-71-C-0025, Southwest Research Institute Report No. AR-805 (May 1971).*

about 25-percent less rear-wheel horsepower than the other two trucks, with a correspondingly lower fuel delivery rate. This truck was therefore effectively derated by comparison to the others and probably would have smoked more otherwise. It was concluded that trucks No. 1 and 3 should be considered more typical.

The results for the LD 465 powered vehicles can be seen to be similar. Truck No. 5 was consistently underfueled during the test and therefore must be considered as effectively derated relative to trucks No. 4 and 6. The more typical trucks No. 4 and 6 gave "a" factors at the 40-percent Federal limit and "b" factors double the 20-percent Federal limit. The smoke levels in table IV represent the averages of several repeated measurements that exhibited satisfactory reproducibility.

Table V summarizes the constant-speed, full-power smoke tests. These smoke levels are averages of several repeated tests. The results for trucks No. 1, 2, and 3 are consistent with those of the previous SWRI study (except for those of the derated engine). The results for trucks No. 4, 5, and 6 show a similar pattern: smoke levels increase as engine speed decreases, reaching a maximum near 50 percent of rated speed.

To put the SWRI results with the Federal compliance test into perspective, table VI gives the Federal certification test data for commercial heavy-duty diesel engines for the 1971 model year.[20] The data for the lower-mileage military vehicles can reasonably be compared to these data. An extensive and very thorough SWRI surveillance study of smoke from in-use heavy-duty commercial diesel vehicles also is available for comparison.[21] A summary would be too lengthy here, but the following comments may be made. In the study, 64 in-use heavy-duty diesel vehicles, covering the spectrum of commercial types, were subjected to smoke inspections (chassis-dynamometer simulation of the Federal test) every 4 months for 2 years. Most of the vehicles remained below the Federal limits into the last months of the surveillance, when engine mileage was frequently over 100,000 miles. Only one engine type failed the Federal "a"-factor test in the entire test program--the Mack ENDT 675 in six trucks. The typical failure was an "a" factor slightly

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[20] *Federal Register, 36, No. 70, Part II (April 1971).*

[21] *J. O. Storment and K. J. Springer, A Surveillance Study of Smoke from Heavy-Duty Diesel-Powered Vehicles, Southwestern U.S.A., Final Report Contract EHS70-109, Southwest Research Institute Report No. AR-909 (June 1973).*

TABLE V. STEADY-SPEED, FULL-LOAD SMOKE TEST DATA ON THREE IN-USE LDS 465 POWERED 5-TON AND THREE IN-USE LD 465 POWERED 2-1/2-TON MILITARY CARGO TRUCKS[1]

Speed rpm	Smoke opacity (%)					
	LDS 465 Truck No.			LD 465 Truck No.		
	(1)	(2)	(3)	(4)	(5)	(6)
2600	7.8	6.5	3.7	-	8.1	22.8
2400	9.2	5.9	13.2	14.5	4.8	16.9
2200	13.2	6.5	14.6	17.4	5.0	19.3
2000	13.5	5.5	15.6	19.1	6.3	22.6
1800	19.4	5.0	26.6	27.4	6.8	27.1
1600	-	-	-	45.8	10.0	35.1
1400	-	-	-	53.9	10.5	38.9

[1] *Adapted from K. J. Springer, Southwest Research Institute Report No. AR-805 (May 1971).*

TABLE VI. FEDERAL CERTIFICATION TEST DATA FOR HEAVY-DUTY DIESEL ENGINES--1971 MODEL YEAR *(from Federal Register, 36, No. 70, Part II, Apr 1971)*

CERTIFICATION DATA FOR HEAVY DUTY DIESEL ENGINES

Two engines of each engine family were tested for certification purposes. The results for each engine tested (engines No. 1 and No. 2) are listed below.

1971 HEAVY DUTY DIESEL ENGINES

(Certification levels)

Manufacturer	Engine family	Engine air aspiration	Models	Smoke emissions: Acceleration mode (percent opacity) Engine No. 1	Acceleration mode Engine No. 2	Lug-down mode (percent opacity) Engine No. 1	Lug-down mode Engine No. 2
U.S. MANUFACTURERS							
Allis Chalmers	25000	Turbocharged intercooled.	25000	30.92	25.47	8.72	6.02
	21000	Turbocharged.	21000	26.47	24.85	18.67	13.51
	3500	Turbocharged.	3500	23.3	23.8	14.2	15.4
Caterpillar-Tractor.	1145	Natural	1145, 1140	20.3	20.8	10.6	10.1
	1150	Natural	1150	23.9	26.4	11.4	13.4
	1160	Natural	1160	20.8	19.8	12.0	7.0
	1673C	Turbocharged.	1673C	11.7	18.1	2.5	3.2
	1674	Turbocharged and after-cooled.	1674	16.7	22.7	1.4	2.9
	1693T	Turbocharged.	1693T	23.7	19.7	3.0	3.0
	1693TA	Turbocharged and after-cooled.	1693TA	33.3	28.3	2.4	1.9
Cummins	855-NA	Natural	NHC-250, NHC-250D, NHH-250, NH-230, NHD-230, NHF-265, NHF-240, NH-160, V-1710.	11.9	10.9	13.7	12.9
	743-NA	Natural	NHE-180, NHE-195, NH-200, NH-220, NH-220D, NHH-220.	15.2	13.5	18.5	15.6

TABLE VI. FEDERAL CERTIFICATION TEST DATA FOR HEAVY-DUTY DIESEL ENGINES--1971 MODEL (Cont'd)

Manufacturer	Engine family	Engine air aspiration	Models	Smoke emissions: Acceleration mode (percent opacity) Engine No. 1	Smoke emissions: Acceleration mode (percent opacity) Engine No. 2	Smoke emissions: Lug-down mode (percent opacity) Engine No. 1	Smoke emissions: Lug-down mode (percent opacity) Engine No. 2
	855-TC	Turbocharged.	NT-350, NTC-335, VT-1710, NHHTC-335, NTC-290, NTC-270-E, NTC-270-CT, NHCT-270, NHCT-CT, NHTF-365, NHTF-295.	28.5	37.3	5.4	7.8
	855-TCA	Turbocharged and after-cooled.	NTA-411, NTA-400, NTA-370, NTA-420, NTC-350, NTC-335, NTC-320, NTC-310.	28.6	27.3	11.1	8.5
	V-903	Natural	V-903, V-320, V-300, V-280	16.5	17.1	18.1	16.6
	VIM/VINE	Natural	V8-265, V8-265D, V8E-235, V8E-235D, V6-200, V6-200D.	13.9	9.6	13.4	8.9
	VAL/VALE	Natural	V8-185-HT, V8-185, V8E-170-HT, V8E-170, V6-140-HT, V6-140.	17.4	9.5	14.9	4.3
	V-504	Natural	V-504, V-378	10.4	9.4	10.4	9.5
	464-TC	Turbocharged.	C-190, C-175	21.8	22.5	2.6	5.6
	464-SC	Supercharged.	C-180	23.4	16.8	13.1	8.2
	VT-903	Turbocharged.	VT-903	10.8	9.2	1.2	1.9
	927-NA	Natural	N-927-270, 260, 250	14.3	15.9	12.8	16.0
General Motors	53N	Natural	3-53N, 4-53N, 6V-53N, 8V-53N.	18.8	23.3	13.8	15.0
	71N (2 Valve)	Natural	6V-71N 2 Valve	4.3	4.1	3.6	3.0
	71N (4 Valve)	Natural	3-71N (4 Valve), 4-71N (4 Valve), 6-71N (4 Valve) 6V-71N (4 Valve), 8V-71N (4 Valve), 12V-71N (4 Valve).	6.1	11.5	2.0	4.0
	71T	Turbocharged.	8V-71T, 6V-71T, 6-71T	26.9	22.6	3.4	4.3
	Toro-flow	Natural	478 (truck) 478 (coach), 637	10.8	9.6	12.7	12.2
International Harvester	DVT-573B	Turbocharged.	DVT-573-B 230,260,280	31.78	32.18	13.44	12.43
	DV-550B	Natural	DV-550B	12.3	13.0	12.4	7.7
	DV-462B	Natural	DV-462-B	13.3	18.5	11.2	14.8
Mack	No. 1 (END 673E)	Natural	END 673E	2.95	3.08	2.49	3.58
	No. 2 (END 707)	Natural	END 707	5.34	6.96	6.01	7.63
	No. 3 (ENDT 675)	Turbocharged	ENDT 673, ENDT 673A, ENDT 673B, ENDT 673C, ENDT 675.	16.37	12.94	6.73	3.84
	No. 4 (END 864B)	Natural	END 864B, ENDD 864 B, END 864C, ENDD 864C.	5.65	6.05	7.71	8.58
	No. 5 (ENDT 864)	Turbocharged.	ENDT-864	6.72	8.53	4.99	5.95
	No. 6 (ENDT 865)	Turbocharged.	ENDT 865, ENDDT 865, ENDTB 865, ENDDTB-865.	26.99	30.86	3.05	9.04
FOREIGN MANUFACTURERS							
Ford (England)	2700 Parent bore.	Natural	380 C.I.D., 253 C.I.D	6.62	6.39	5.79	7.44
Perkins (England)	No. 1	Natural	4.236, 6.354, NA-120	14.12	17.98	18.02	18.98
	No. 2	Natural	V8.510	9.0	16.5	7.3	14.1
AB Scania Vabis (Sweden)	No. 1 (D-8)	Natural	D-8 (END 475)	7.22	5.67	6.72	9.14
	No. 2 (DS-8)	Turbocharged.	DS8 (ENDT 475)	6.89	10.56	1.79	4.05

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greater than 40-percent opacity. The worst "b"-factor failure observed in the entire test program was about 31-percent opacity from a dump truck powered with an International Harvester DV 550 B. Many of the vehicles passed the proposed 1974 Federal "a"- and "b"-factor limits (20- and 15-percent opacity, respectively) well into the last stages of the study.

7.2 Indications of Interviews and General Summary of Problem

During this study, interviews were conducted to fill out the presentation of published test reports, with (1) engineers having long and detailed technical experience with diesel smoke and military vehicles, (2) vehicle-maintenance personnel, and (3) smoke-limit-enforcement officials having considerable contact with these military vehicles.

Engineers familiar with the multifuel 465 engine essentially unanimously concur that its smoking characteristics place it among the heaviest smoking compression-ignition engines in widespread use. Although no one is prepared to entirely discount the efficacy of a serious maintenance program in correcting this problem to some degree, little optimism is evident in this regard. It is generally felt that maintenance can only contribute to, but not provide, an overall solution. Apart from maintenance, only engine derating, turbocharging of naturally aspirated units, and antismoke fuel addititves appear to be alternatives to reduce the vehicles' high smoking. Turbocharging and additives are certainly practical. However, retrofit turbocharging of the entire fleet of LD 465 2-1/2-ton military cargo trucks might cost too much. Engine derating in the form of effective reduction of available rear-wheel horsepower seems utterly impractical.

Moreover, people directly concerned with human factors emphasize that the typical military-rig operator lacks enough experience and desire to practice low-smoke driving habits, which are essential for driving a high-smoke vehicle.

The problem involved therefore appears to have two major aspects: (a) the overwhelming bulk of the vehicles involved present an inherent difficulty to a program of smoke control by maintenance, and (b) this situation is further aggravated by a general failure of the vehicle operators to take account of the smoking tendencies of these vehicles. In contrast, however, the military is in a unique and advantageous position with respect to administering to these problems. Unlike Federal and State authorities who are obliged to seek the cooperation of independent agencies in dealing with these problems, either through cordial or coercive means, the military is in essential administrative control of the entire situation. This advantage should dictate the overall approach to the problem.

8. SUMMARY AND DISCUSSION OF ALTERNATIVE SOLUTIONS

The multiplicity of techniques and equipment that have been developed for the measurement of diesel exhaust smoke reflects the number of different interests connected with such measurements and the fact that reliable standards are still being sought. Questions of accuracy, correlatability, and applicability still exist with regard to smoke meters and the choice of an appropriate one for a given task. Nevertheless, intelligent choices and reasonably satisfactory measurements are possible. Commercially available are good-quality field-use smoke meters that can be easily operated and maintained by relatively unskilled personnel. However, some degree of training would be required in the proper use of these instruments. The portable Celesco and Wager instruments, for example, fall into this category. Also commercially available are test laboratory instruments that can furnish detailed transient and steady-state smoke records of engine operation. The USPHS and White end-of-line smoke meters and the Celesco and Wager in-line smoke meters are examples. These instruments require more skill to operate and maintain: a well-trained maintenance or laboratory technician would be called for. But they are capable of greater accuracy and permit more flexibility in use than the simpler portable instruments.

There are many engine and vehicle smoke-test procedures, mainly because diesel vehicles vary widely in smoking characteristics and various interests prevail in their use. The choice of an appropriate procedure for a given task must be based on an explicit recognition of these factors. The Federal certification procedure, for example, combines a general measure of full-power lugdown and acceleration smoke. It is well suited for the general characterization of the overall population of automotive diesels in the United States. For European vehicles, which consist mainly of naturally aspirated units, acceleration smoke is not definitive. Thus, a series of steady-speed, full-power smoke tests seems more appropriate. Where practical considerations do not permit such detailed tests, detail and expediency must be compromised.

The smoke-control programs of enforcement agencies in the United States have generally succeeded. Their major difficulties are mainly administrative, not technical. Their effectiveness depends on obtaining the cooperation of often-resistive independent agencies, such as commercial trucking companies. Also, the legal basis of enforcement must be carefully developed. Regulations must address the actual enforcement problems and withstand court tests. The history of these activities also suggests that the technical basis of the program need not be especially sophisticated or even very good for the program to be

effective. The opposite is true of maintenance programs. Their success is based on effective smoke evaluation and correct identification of engine malfunction when smoke is excessive. Even here, though, a great deal of benefit often accrues from the attention and awareness of smoke that is prompted by the mere existence of a program.

Two specific problems are faced by the Army in attempting to control smoke. (1) Most vehicles in the fleet tend to smoke at high levels. (2) Military vehicle operators have relatively little experience with and are generally not habituated to proper driving technique for diesel rigs. These two factors tend to aggravate each other. The Army also has two substantial advantages in attacking these problems. Since it has effective administrative control over the entire operation, from driver training and enforcement to the setting of maintenance policies, the Army has great flexibility and many options in choosing solutions. The relatively small number of different engine-vehicle combinations in the major part of the fleet also can be exploited. This makes it possible to deal intensively and, therefore, more effectively with the smoke problem of only a few types of vehicles.

In four basic areas, a solution to these problems can be sought: training, enforcement, maintenance, and vehicle modification.

8.1 Training

Driver training appears to be potentially the most fruitful approach to the problem. The idea and goal of this approach would be to include methods in the driver-training program that promote a high level of smoke awareness and habitual use of driving techniques that minimize vehicle smoking. A meter readout, proportional to smoke production, on the dashboard of the vehicle cab would alert the driver to his vehicle's smoke production, as do the tachometer for engine speed and the speedometer for vehicle speed. Such an instrument would clearly provide an ideal basis upon which to develop the training methods and could be quite efficacious in developing habits of low-smoke driving. It might, in fact, be necessary to provide such devices only on training vehicles and thereby avoid the expense of outfitting the entire fleet with them. If such a system were provided for all of the troublesome fleet vehicles, both the organizational maintenance and enforcement requirements for a smoke meter would be fulfilled. In addition, the use of such a smoke meter would require virtually no special skills in vehicle operators and enforcement personnel.

However, a smoke meter that could be used in this manner is not available commercially, and such an application of smoke meters seems never to have been seriously contemplated. Hence, the choice is either to expend the effort in developing such a system or to consider alternative training aids.

The development of a permanently installed vehicle smoke meter appears feasible. Two basic difficulties are connected with furnishing such a system: (1) Soot-deposit and temperature-effect problems are unavoidable with a system that is proximate to the exhaust smoke and has continuous-duty requirements. (2) Ruggedness and weatherproofing are required for an externally mounted vehicle sensor device. There are several ways that these problems can be dealt with. The next few paragraphs describe approaches that seem particularly promising.

8.1.1 Optical Backscatter Sensing

The most obvious solution of the problems of soot contamination and heat degradation is to move the sensor system away from the exhaust smoke. This approach requires a remote, single-ended technique to measure smoke density. Such a technique could be provided by the use of optical backscatter methods. The basic idea is to shine a beam of light at the smoke plume and take the amount of detected backscatter signal as a measure of the smoke density. This measurement could be done with a composite sensing system consisting of an optical transmitter and companion detector located at some convenient distance (say, 1 to 3 ft) from the smoke plume. The sensor would contain a pulsed light source (a semiconductor laser or LED, depending on transmitter power requirements) and a solid-state photodetector, together with the transmitter and detector optics. Electronic processing circuitry would be distributed between the sensor and the vehicle cab meter as determined by the selected design options and convenience. Electrical power requirements would be furnished by the vehicle battery. The system envisaged is similar in many respects to an optical proximity sensor recently developed at HDL.[22] Many of the design considerations pertinent to this development would apply as well to the system being considered here.

The basis of the smoke-density measurement is in the relation between it and the detected backscatter signal. This relation is mediated by two parameters characterizing the smoke as an aerosol--the volume backscatter coefficient, $\mu(\pi)$, and the extinction coefficient, K--and various parameters characterizing the system. Several theoretical calculations have been performed that relate these parameters to the detected backscatter signal.[22] These have in turn been successfully applied to the design of optical ranging systems where interposed aerosols present problems of discrimination. The backscatter and attenuation coefficients are directly related to the smoke density--they also depend on the soot-particle-size distribution and

[22] *Z. G. Sztankay, Analysis of a Slant-Range Optical Proximity Sensor (U), Harry Diamond Laboratories TR-1625 (July 1973). (CONFIDENTIAL)*

index of refraction and on the transmitter wavelength. The overall analysis suggests that the relation between the smoke density and the detected backscatter signal is linear for sufficiently low density, but saturates for high smoke density. That is, the backscatter tends to become independent of the smoke density for sufficiently dense smoke. Instrumentation has been developed at HDL to measure the aerosol parameters $\mu(\pi)$ and K.[23,*] This instrumentation has recently been used for many such measurements on various aerosols including clouds, fog, and smoke. Some of these data have been analyzed, and the rest--virtually all of the smoke results--should be reported soon. Analysis of these data may permit some verification of the above analysis.

8.1.2 Gas Dynamic-Air-Sheath Entrainment

An optical transmission measuring system, similar to systems used in many commercial smoke meters, could be used for a permanently installed device. But the overall design must include sufficient smoke-deposit protection and thermal isolation of the critical system components. A promising approach is based on entraining a flowing air sheath at the exhaust gas boundaries near the transmissometer components. A nozzle shaped as shown in figure 18 is formed at the terminus of the exhaust line. With appropriate dimensioning and contouring, such a nozzle would produce no back pressure effects (by maintaining the same cross-sectional area) and would give a relatively high and roughly uniform exhaust gas velocity across the small dimension of the flow. With fresh air allowed to impinge on the issuing exhaust flow, the gas dynamic effect of momentum sharing, coupled with the relatively high boundary velocity of the exhaust gas, would set up a substantial air flow patterned as shown in figure 19. This configuration closely resembles that of a fluidic amplifier in the interaction area, as described by Kirshner[24] and studied for entrainment factors by Drzewiecki and Goto.[25,26] The air flow is energized by the

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[23] *D. A. Giglio, B. J. Rod, and H. M. Smalley, Nephelometer for Mapping of Backscatter and Attenuation Coefficients of Clouds, Harry Diamond Laboratories TR-1660 (February 1974).*

[24] *J. M. Kirchner, ed., Fluid Amplifiers, McGraw-Hill Book Co., New York (1966).*

[25] *T. M. Drzewiecki, and J. M. Goto, An Analytical Model for the Response of Flueric Wall Attachment Amplifiers, Fluidics Quarterly, 5, No. 1 (January 1973).*

[26] *T. M. Drzewiecki and J. M. Goto, Reattached Jet Response to Input Pressure in a Non-Loaded Fluidic Bistable Configuration, Fifth Cranfield Fluidics Conference, Uppsala, Sweden, 3 (June 1972).*

**D. Mary (HDL), unpublished data.*

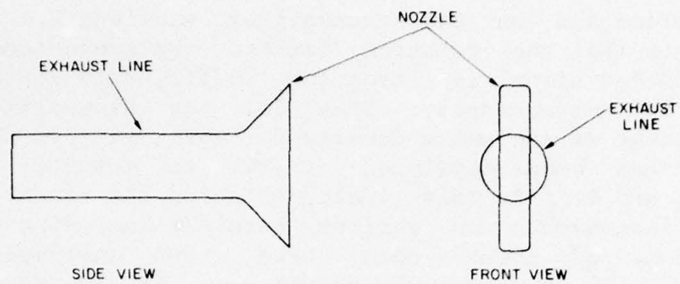

Figure 18. Exhaust-line nozzle configuration for proposed permanently installed vehicle smoke meter based on gas dynamic-air-sheath entrainment and optical transmission measurement.

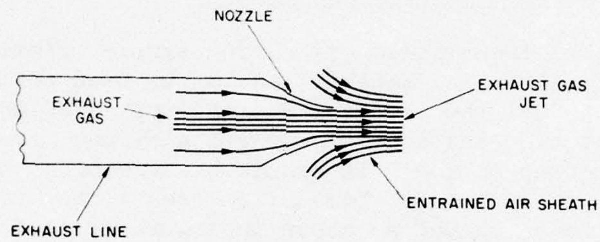

Figure 19. Entrained-air-flow pattern in plane at right angles to long dimension of exhaust-line nozzle.

exhaust gas flow itself, and no external source of air pressure is required other than the ambient atmosphere. To turn this effect to advantage in a permanently affixed exhaust-pipe smoke meter, an air induction system would have to give a stable means of drawing fresh air, independent of breezes, drafts, etc., near the exhaust outlet. Figure 20 shows a possible arrangement intended for mounting atop the exhaust stack. Also required would be the provision of a weather-tight mounting arrangement for the optical-electronic components of the transmissometer. These would be mounted in the region of heaviest air entrainment, so that maximum soot deposit protection and cooling effect would be provided. A system of this sort could work continuously with relatively little maintenance.

8.1.3 Venturi-Effect System

Another approach involves the exploitation of the Venturi effect, as shown in figure 21. With this arrangement, a small restriction in the exhaust pipe is envisaged near the transmissometer components to set up appropriate pressure gradients for air induction. The major consideration is to generate sufficient air flow to protect

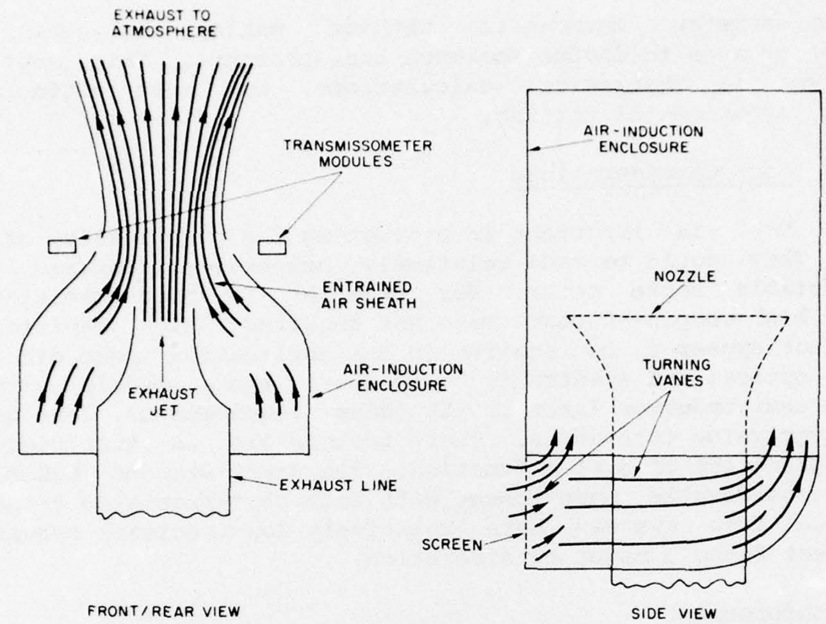

Figure 20. Possible overall configuration for permanently installed vehicle smoke meter using air-sheath entrainment.

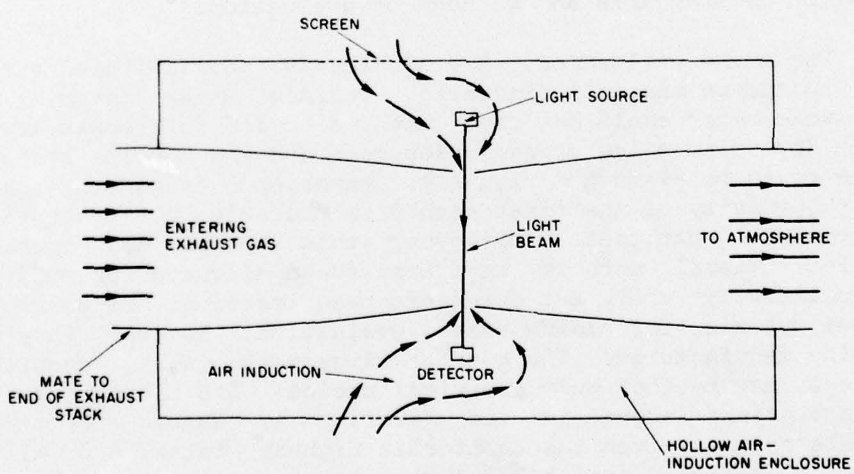

Figure 21. Possible end-of-stack smoke-meter configuration for permanently installed vehicle device using Venturi effect for component-protecting air induction.

the transmissometer components without making the exhaust pipe restriction such as to induce too much back pressure. This question can be explored via theoretical calculations, but must ultimately be answered by experimental testing.

8.1.4 Cost Considerations

Cost is important in evaluating the practicality of these systems. They could be made relatively inexpensive (compared to the Celesco portable smoke meter, for example) if high-precision and, therefore, high-component cost were not required. High precision would certainly not appear to be required in the application under discussion. Costs of optical and electronic components range widely with such factors as semiconductor laser or LED power requirements, lens quality, and component value tolerances. These factors are in turn tied to the required precision of system function. The Harry Diamond Laboratories has had considerable experience with such cost-precision trade offs, since typical fuze systems have relatively low-precision requirements with low cost being a major consideration.

8.2 Enforcement

The enforcement of smoking limits by the Military Police is another possible approach to smoke reduction. This approach requires a consideration of standards and methods of evaluation.

For smoke evaluation, two alternative possibilities exist, in addition to the permanently installed vehicle smoke meter. (1) A portable smoke meter could be used with a brief full-power low-speed smoke test (by using a low transmission gear and the service brakes), or (2) smoke could be evaluated visually. Experience suggests that the apparent objectivity of the first method is probably not necessary for an enforcement operation. Moreover, this method has operational difficulties. Visual methods have been found adequate for enforcement and are relatively easy, but observers need training. Filmstrip smoke guides seem superior for aiding visual evaluation. However, they are no longer being manufactured. The pocket Ringelmann chart, despite its shortcomings, may be the only practical choice. Its widespread use and general acceptance argue in its favor. A degree of training intermediate to that given the California Highway Patrol and California Air Pollution Control District Inspectors seems appropriate.

Of course, if a permanently installed vehicle smoke meter were standard equipment on the vehicles subject to enforcement, a quantitative reading of the smoke level would be readily available. Then, a very loose visual criterion could be used by the Military Police to indicate the need for further investigation. If warranted, he could then board the vehicle for an inspection test drive, using the dashboard smoke meter for an objective evaluation of the smoke level.

Two cautions should be observed in the structuring of an enforcement program. They both contribute to the difficulties that could arise if overzealous Military Police enforce a standard that is difficult to meet. A standard must be chosen reasonably and applied with discretion. The choice of a rigid standard would have to be based on the knowledge of what smoking behavior can reasonably be expected from military diesel vehicles, assuming they are maintained and driven properly. Since this knowledge can be obtained only by driver-training and maintenance approaches to smoke reduction, a flexible standard seems initially the most suitable. Also, enforcement alone cannot affect the smoke problem as desired. It should be considered supplementary to other approaches that deal more directly with the problem's source.

8.3 Maintenance

The effectiveness of maintenance to significantly reduce the smoking of Army automotive diesels has been questioned. The essential aspects of the problem seem to lie elsewhere. It would, however, be a mistake to neglect maintenance altogether. If smoke reduction procedures are not included in the maintenance of these vehicles, the problem would be further aggravated. Smoke-control maintenance can be done by the vehicle operator himself or by the higher-level maintenance units. This work can be done in response to a smoke-meter indication or routinely at specified intervals. In either case, it involves the inspection, repair, and adjustment of either the fuel-delivery or air-induction system.

Organizational maintenance permits the closest degree of control over vehicle smoke, provided that the vehicle operator checks the smoke production vigilantly. This would be best accomplished through a combination of training and the provision of a smoke meter. It would be preferable from an operational viewpoint to provide a permanently installed vehicle smoke meter with a dashboard meter readout. With little effort other than attention, the driver would have an ever-present indication of the smoke production. Deterioration in smoke performance would become immediately evident. Lacking such an on-board meter, the driver could use a portable smoke meter. A driver's periodic smoke-meter test of the vehicle would presumably point out deteriorations in the smoke performance. However, an appropriate smoke test would have to be devised.

Initially, the smoke test could be a modification of the New Jersey truck procedure, so that the test engine speed involved is made to fall in the maximum smoke range for the Army's diesels indicated tentatively in the SWRI studies.[18,19] Also, a simple acceleration test under specific vehicle loading conditions could be devised to apply to the turbocharged rigs. Ultimately, the best way to determine an appropriate test would be to study smoke, as done by SWRI, on a statistically significant number of fleet vehicles. This study would yield sufficient information to devise a smoke test specifically suited to the military vehicles.

Above the level of organizational maintenance, smoke meter and associated test procedures should be included in the maintenance routine. Doing so would provide a continuity of viewpoint regarding smoke throughout the maintenance echelons, as well as thorough, if infrequent, additional vehicle-smoke inspections. Also, one of the more elaborate smoke meters should be considered for this part of the maintenance operation. The personnel and environment at this level appear to lend themselves to the competent and efficient use of such instruments, and the added scope of usefulness made available may prove of some assistance in other aspects of the maintenance operation.

Finally, maintenance procedures alone are unlikely to have the desired impact on the smoke problem. An improved driver-training program supplemented by a well-thought-out maintenance program appears to be what is needed.

8.4 Vehicle Modification

Turbocharging is a common retrofit modification used on naturally aspirated engines to reduce smoke and improve power. When smoke reduction is the major goal, turbocharging without power improvement characterizes the modification. This approach works well in limiting steady-speed smoke, reductions of 50 percent not being unusual, but the approach is ineffective for acceleration smoke and often worsens it. Several engine manufacturers offer turbocharging kits of this sort. For example, the Cummins turbocharging retrofit kit for its NHC-250 engine quite effectively reduces cruise smoke; this retrofit costs approximately $1000 installed.

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[18] *K. J. Springer, Baseline Exhaust Emissions from U.S. Army M54A2 LDS 465 Powered Five-Ton Trucks, Final Report Contract No. DAAD05-67-C-0361, Southwest Research Institute Report No. AR-690 (April 1969).*

[19] *K. J. Springer, Preliminary Survey of In-Use Army Vehicle Emissions Characteristics, Final Report Contract No. DAAD05-71-C-0025, Southwest Research Institute Report No. AR-805 (May 1971).*

Engine derating is perhaps the most widely used modification for smoke reduction. The available engine horsepower is reduced by such modifications as injector replacement, fuel-pump calibration, and reduction of fuel-delivery pressure and seems an ill-advised approach for military vehicles.

Dual fuel or fumigation systems, which increase the efficiency of fuel combustion, have found limited application for fuel economy and smoke reduction. Typically, these systems meter a small amount of subsidiary fuel, such as liquified petroleum gas, into the intake manifold to initiate precombustion reactions that help the fuel burn better. Although this method reduces smoke somewhat, the need for a dual fuel supply has limited its popularity. A similar approach, without vehicle modification, is the use of antismoke fuel additives. Barium-based additives have sometimes quite effectively reduced smoke. The principle of their operation is not entirely understood, however, and possible health hazards caused by their metallic emissions have not yet been satisfactorily explored.

Several cosmetic methods have been tried for changing the appearance of the exhaust smoke plume. Some systems dilute the exhaust smoke by drawing fresh air into the exhaust pipe. Others are end-of-stack diffuser devices. They have generally proved unsatisfactory and have often made smoke more noticeable.

9. RECOMMENDATIONS

Five recommendations can be drawn from this discussion:

(a) Of most importance, an improved driver-training program is needed to increase the general awareness of the smoke problem among vehicle operators and habituate them to proper, low-smoke driving techniques. They could be trained best with a permanently installed vehicle smoke meter, having a dashboard meter readout, as a training aid. Although systems able to perform this function are not commercially available, their development seems feasible along several lines.

(b) Since many of the vehicles in the military fleet tend to have a high smoke level, means should be provided to rapidly identify the need for repairs or adjustments that pertain to smoke production. Such means would be most effective if used by the vehicle operators, since they contact the vehicle daily. An operation of this sort would be best facilitated by use of a permanently installed vehicle smoke meter. With such an instrument, deterioration in the smoke performance of a vehicle would become immediately known to the driver without his having to

perform any special tests. He could then inspect and repair the vehicle himself or refer the problem to a better-equipped maintenance unit. Such a smoke meter would also continuously aid good driving habits and, in turn, produce a number of subsidiary benefits, such as improved fuel economy and longer effective engine life.

(c) Lacking permanently installed vehicle smoke meters, the next best choice for a maintenance tool would be a good-quality, portable smoke opacimeter. The use of this instrument by vehicle operators would have to be integrated with a well-thought-out maintenance program, involving routine vehicle inspections using a smoke-test procedure suited to the military fleet. The program and test procedures would be best selected on the basis of a careful evaluation. However, tentative choices of procedures could be based on information contained and referred to here.

(d) If the maintenance approach outlined in recommendation (c) were implemented, both a smoke-meter and associated test procedures should be provided for the upper-level maintenance units, as well. Doing so would be necessary for continuity of viewpoint and approach to smoke control throughout the maintenance levels. One of the laboratory-type smoke meters should probably be selected, for conditions at this level would permit its use, and it could contribute to the overall operation. Whatever choice were made, smoke meters of the same manufacturer should be used for all levels of maintenance, to eliminate most questions of correlation.

(e) Enforcement of smoke limits by the Military Police could help encourage the vehicle operator's cooperation with the training and maintenance programs. Although a portable smoke meter could be used in enforcement, its relative operational complexity and apparent lack of necessity would argue against it. Visual smoke evaluation applied very discreetly could aid enforcement. Its effective implementation would require the training of enforcement personnel in this method and in the philosophy and goals of the enforcement procedure. Ringelman charts are widely used and accepted. Although they have many drawbacks, they seem to be serviceable for visual smoke evaluation and are readily available. If a smoke meter were permanently installed on a vehicle subject to enforcement, it could allow a quantitative reading of the smoke level. On observing a vehicle, the Military Police could use a very loose visual criterion to indicate the need for further investigation. If warranted, he could then board the vehicle for an inspection test drive, using the dashboard smoke meter as a basis for citation. He could readily check the calibration of the meter and attach a strip-chart recorder to obtain a permanent record.

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